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THE ECONOMIC IMPACT OF MAGNESIUM CHLORIDE DEICER ON CONCRETE BRIDGE DECKS:

A STUDY FOR THE MONTANA DEPARTMENT OF TRANSPORTATION

Prepared for:

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In 1997 the Montana Department of Transportation's Bridge Bureau noticed a significant increase in the amount of chloride in certain bridge decks around the state. The Department retained the consulting firm of Reid Crowther & Partners to perform a study of the cause of the increase.

This report is a result of that study. The Department's Maintenance Division has concerns about the validity of the study. The following page describes those concerns. The Department's Engineering Division accepts the results of the study, at least in part for the reasons that follow immediately after the Maintenance Division concerns.

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DISCLAIMER

MDT's Maintenance Division, does not agree with the conclusions drawn by this report.

We do not dispute that chlorides, regardless of the source, are not good for bridge decks. We do, however, have concerns with the assumptions made and conclusions drawn in the Reid-Crowther report.

Points of Concern;

- Saltese, mileposts 0 to 30, is the top of Lookout Pass and due to considerable climactic differences, receives twice the precipitation of the other test section. Thus, it is subjected to chlorides more frequently and for greater periods of time in any given year.
- Saltese bridge decks receive five times the chloride loading than the other test section due to colder conditions and heavier precipitation.
- Saltese uses magnesium chloride at the approximate average rate of .61 lbs. dry weight per square yard per year. In addition, sodium chloride is applied at the approximate average rate of 2.88 lbs. per square yard per year resulting in a total of **3.49 lbs.** of dry weight chlorides. Superior, the other part of the test section, applies an approximate total of **.67 lbs.** of dry weight sodium chloride per year. Logically, Saltese bridges would have higher chloride levels because of the increased loading.
- It has yet to be determined what source of chloride (sodium, magnesium or calcium) is the most detrimental to the life of bridge decks. There are new generations of corrosion inhibitors for chlorides that may reduce their accumulation, migration and impact on concrete and steel embedded in concrete.

  Concerns for MDT's infrastructure has justified the start of a long-term research project to find answers to concerns raised by this report. However, new generation concrete, coatings and additives must play a partnership role in the prevention of chloride contamination as does the continued search for low impact chemicals used for providing safe winter highways.
- **Finally, the conclusions drawn in this report, are erroneously based upon the source and quantity of the chloride ions being attributed solely to magnesium chloride applications. The source of the chloride ions can't be accurately determined when high levels of sodium chloride applications are contaminating the sampling results.**

For more detailed information feel free to contact;
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The Maintenance and Engineering Divisions differ on the validity of this study. The Maintenance Division points out that although the Saltese and Superior Sections of Interstate 90 are roughly the same length, the Department plows four times as many lane miles in Saltese as in Superior. They therefore say the Saltese Section receives four times the chloride-containing chemicals. Maintenance adds that the Saltese Section also applies four times as much sodium chloride as magnesium chloride, while the Superior Section saw only sodium chloride. The Maintenance Division assumes that this report must be inaccurate, because

- with four times as much chloride applied, of course the Saltese Section would display higher levels than Superior
- with four times the sodium chloride as magnesium chloride, the study cannot possibly identify the higher chloride levels as the result of magnesium chloride.

The Engineering Division takes the position that although reasonable, the points above do not apply in this situation.

Chloride Contamination Process

Chloride contamination levels in the top six millimeters of the decks change seasonally. Chloride levels climb in winter with deicer application. They fall as summer rains flush chlorides from the concrete. Chloride levels below that zone show more stability. Since the effects of rain do not reach below there, chlorides accumulate. Repeated deicing adds chlorides to the top. They gradually diffuse through the concrete. This slow diffusion means highest chloride levels at the top of the deck, decreasing with depth.

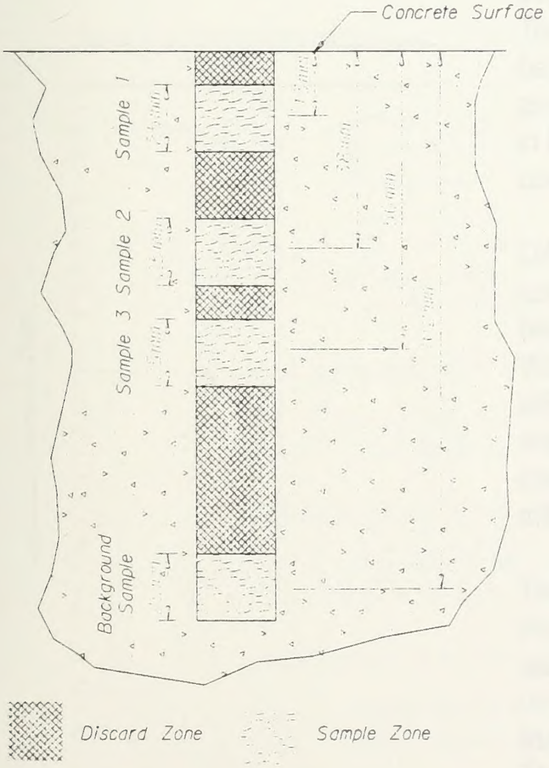

Figure 1 ~ Test Hole Sample and Discard Zones

All concretes contain some chloride. This chloride comes from aggregate, cement, mix water, or concrete admixtures. Reid-Crowther called this "background" chloride, or the chloride level before the effects of deicing chemicals.

Sampling and Testing Process

Figure 1 shows how workers took samples. Using a 32 mm-diameter drill bit, they drilled and discarded the first 6mm of deck. The seasonal fluctuation of chlorides in that zone makes measuring them pointless. The workers continued collecting the powdered drilling residue from the other sample zones in Figure 1. The bottom sample established background chloride level.

The workers collected 400 samples. Reid Crowther hired a laboratory to test each of them and record its chloride level, then performed a statistical analysis on the results. Their statistical analysis showed higher levels of chloride in samples taken in driving lane wheel paths from Saltese Section bridges than in ones from the Superior Section. The difference between Sections increased with sample depth.

Expected Research Results

If the additional chloride applied to Saltese Section bridges entered the concrete, we would expect a large difference from the Superior Section. The difference would be greatest near the deck surface, and would decrease with depth as the applied chlorides had less effect and the chlorides approached the background level. Figure 2 shows this expected relationship between the chloride levels of the two Sections.

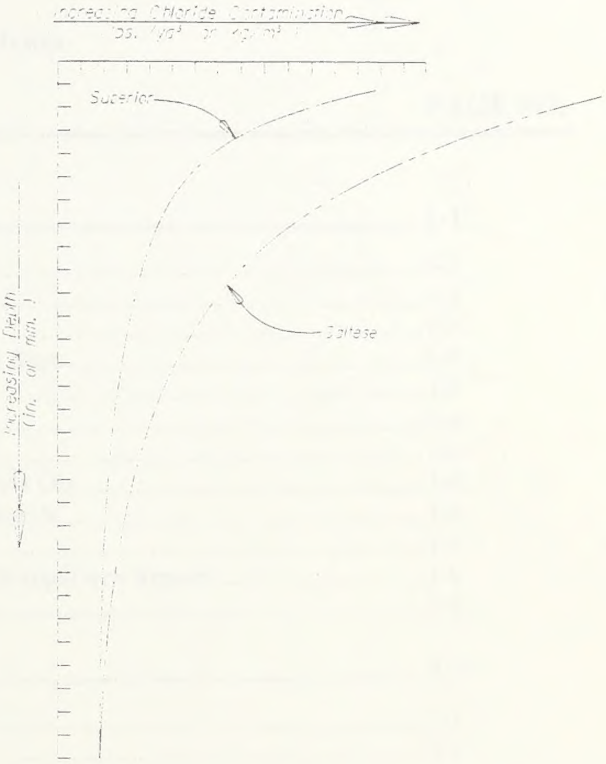

Figure 2 ~ Expected Relative Chloride Levels

Actual Research Results

The test results indicate the opposite relationship. As Figure 3 shows, the deck chloride levels in both Sections are nearly the same near the surface. However, the Saltese chloride levels increase more rapidly as the depth increases, indicating that these structures have a higher diffusion rate than that of the Superior structures. (Note: Both Figures 2 and 3 represent chloride levels after subtracting background chloride. They show only effects of applied chlorides.)

Figure 3 leads to one conclusion. The amount of chloride entering the concrete below the six-millimeter zone remains the same between the two Sections, regardless of application rate. Only part of the chloride penetrates the deck. The concrete below that zone receives chloride only from above. Since the peak is the same in both Sections, we know that the decks in both start at the same contamination.

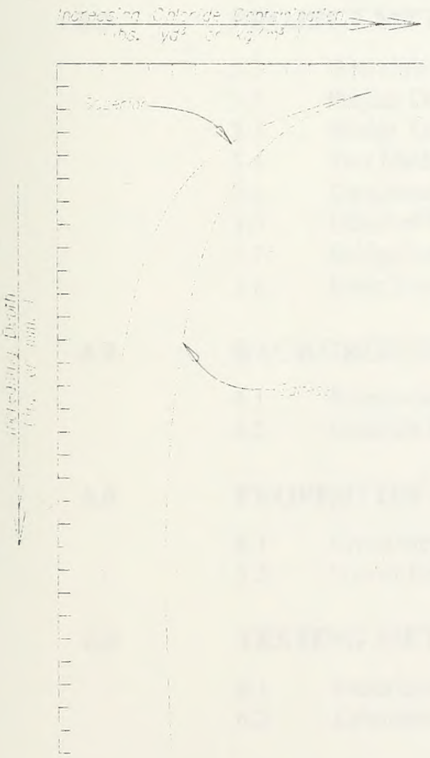

Figure 3 ~ Actual Relative Chloride Levels

Diffusion of chlorides through concrete depends on properties of the concrete such as porosity and permeability and on environment. The two Sections share common concrete properties and environment. We don't know the cause for the common peak level of contamination, although we can guess. For example, the greater amount of snow and ice in the Saltese Section may flush away excess deicing chemical when it melts. Perhaps summer rains flush the six-millimeter zone, so excess chloride never enters the deck.

The reason for this relationship will have to wait for further research. Regardless of the cause, we know the concrete's environment is the same below the six-millimeter zone in both Sections. The only remaining differences are the use of magnesium chloride and the associated higher chloride level in one Section and not the other. That evidence leads the Engineering Division to accept this report's conclusion.

The Economic Impact of Magnesium Chloride Deicer on Concrete Bridge Decks: A Study for the Montana Department of Transportation

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SECTION 1.0

EXECUTIVE SUMMARY

SECTION 1 EXECUTIVE SUMMARY

Reid Crowther & Partners (RCPL) was retained by Montana Department of Transportation (MDT) to conduct a study on the potential economic impact to Montana bridges of switching to magnesium chloride based from sodium chloride based chemicals. This study focuses on half of the overall picture in that it only addresses the bridge costs resulting from magnesium chloride use and does not address the benefits of anti-icing practice.

The economic impact resulting from two possible pavement management scenarios is assessed:

1. anti-icing practice limited to only those roads currently treated with magnesium chloride.
2. anti-icing with magnesium chloride in place of conventional deicing practice on most of the Montana road system.

1.1 INTRODUCTION

In cold regions the policy of maintaining bare skid-resistant road surfaces in winter has important public benefits in the form of reduced traffic accidents and increased productive time resulting from higher safe driving speeds. These benefits will increase in the future as populations, AADTs, and allowable speed limits continually increase.

Magnesium chloride is a highly effective winter roadway anti-icer that has been coming into increasingly common usage in recent years. MDT has been evaluating the effectiveness of magnesium chloride and other anti-icing and deicing materials on selected roads during the past ten years. Properly used, this liquid applied chemical is more effective, especially at low temperatures, than conventional sodium chloride deicers in preventing formation of surface ice and maintaining the skid resistance of roads and bridges. A side effect, however, is that each magnesium chloride molecule contains two chloride atoms instead of the single chloride in a sodium chloride molecule. Regardless of source, free chlorides diffuse through concrete, destroy the natural passivation of concrete for reinforcing steel, and initiate a deterioration process that reduces bridge life. The effect is most significant to decks, the most exposed structural bridge component, the roof that shelters the underlying bridge components.

1.2 BACKGROUND

1.2.1 Deicing versus Anti-Icing

Deicing chemicals are important in maintaining bare, skid-resistant pavements and reducing accidents in winter conditions. Maintaining pavement traction becomes even more important as traffic volume and allowable speeds increase, such as on the Interstate road system.

Sodium chloride has been an important product in the evolution of the bare pavement policy. Sodium chloride or rock salt is a classic deicer, which attacks icy road surfaces and restores traction by melting the ice. The ice-melting abilities and costs of different chemicals vary considerably. The most cost-effective chemical has traditionally been rock salt, sodium chloride, which has been used in Montana since the late 1970's.

Recent developments in technology have attempted a different approach to prevent the formation of roadway ice by applying anti-icing treatments, such as those containing the liquid forms of calcium or magnesium chloride.

1.2.2 Product Approval

The MDT deicer/anti-icer product approval tests include one to measure the corrosion of exposed steel but do not assess potential corrosion of steel in reinforced concrete. The electro-chemical process of reinforcing steel corrosion in concrete is entirely different than the corrosion process for exposed steel. Similarly, there are no current approval tests to measure the potential concrete problem of surface scaling. The Strategic Highway Research Program has addressed these needs in publication SHRP-H-332.

1.2.3 Side Effects of Chloride Based Chemicals

The various side effects of chloride-based deicers include corrosion of exposed steel, such as cars and light poles, as well as depassivation and corrosion of embedded steel in structural concrete. In a similar manner to sodium chloride, magnesium chloride dissolves in water solution and produces chloride ions, except with magnesium chloride there are twice as many chloride ions per molecule. When chloride ions are absorbed into porous concrete bridge elements, they initiate the corrosion of embedded steel, leading to progressive loss of load carrying capacity, and expensive remedial actions. Concrete's high alkalinity normally protects embedded structural steel from corrosion. Free chloride ions destroy the natural protection and initiate steel corrosion and concrete deterioration, which destroys structural load carrying capacity.

1.2.4 Concrete Permeability and Chloride Diffusion

Normal concrete is a naturally permeable material. The permeability results from capillaries or connected voids that are left by the evaporation and bleeding of the extra mixing water that is needed for placing workability but is not consumed by the cement hydration chemical reaction. Normal concrete readily absorbs water and other deleterious chemicals such as chloride ions. Chloride ions naturally diffuse in a direction away from high chloride concentrations to areas of lesser concentration. The rate of chloride diffusion is expressed mathematically by Fick's Second Law, which relates the driving force of diffusion and the surface chloride concentration to other diffusion rate parameters, such as time and the concrete diffusion coefficient.

1.3 OVERVIEW OF PROJECT METHODOLOGY

The work included the following tasks:

- Background investigation and literature search
- Bridge test site selection, ten bridges exposed for ten years to each of the two road treatment chemicals, sodium chloride and magnesium chloride
- Chloride content sampling of the twenty selected bridges, cover depth measurements
- Laboratory testing of chloride ion content (400 tests)
- Adjust test data to remove background chlorides (chemically combined chlorides not available to promote corrosion)
- Find and remove data outliers (1) and explore data for trends
- Do statistical analysis for validation of hypotheses
- Analyze magnesium and sodium chloride absorption and diffusion rates in concrete
- Use the chloride diffusion results to assess magnesium chloride impact on bridge service life, and investigate factors such as bridge age and cover depth
- Categorize the Montana bridge inventory according to expected remaining service life with conventional deicing practice
- Determine the future annual MDT bridge replacement costs with conventional deicing

- Use the service life findings to analyze the long term economic impact of magnesium chloride on Montana bridges in two scenarios:
  1. if magnesium chloride anti-icing is continued only on roads currently being treated,
  2. if magnesium chloride were to be used on the portion of the overall Montana bridge inventory where deicing is currently considered necessary,
- A secondary goal was to use chloride test data to quantify the effect (success) of some existing MDT bridge deck repairs on deck service life

1.4 BRIDGE TEST SITES

The methodology of this project involved testing appropriately selected bridges in the real world rather than ones subjected to laboratory test conditions. The work involved taking samples from concrete bridge decks that had been primarily exposed to either magnesium anti-icers or sodium chloride deicers for relatively long periods of time. Since this study involves predicting future conditions and costs, and since future use of chemical treatment will increase, a heavily treated section of road was selected for testing.

A 61.8-mile portion of divided Interstate 90 west of Missoula contained a large number of bridges and half the road had been exposed to magnesium chloride anti-icing while the other half to conventional deicing practice. The bridges were constructed between 1960 and 1984 of reasonably similar structural designs, construction standards and concrete materials. The volumes of traffic along this stretch of Interstate 90 were relatively constant and other site conditions reasonably similar. The final selection of twenty bridge deck test sites was done by the testing crew in the field on the basis of site conditions related to public and worker safety, clear sight distance and acceptable deck width.

1.5 SAMPLING AND TESTING

1.5.1 Field Concrete Sampling

The field-sampling involved taking twenty powdered concrete samples from three depths and forty to sixty top mat reinforcement cover depth measurements at each site. All chloride samples were taken at representative, typical, non-cracked deck locations using a template for guidance. Half the samples were taken on the right lane right wheel path and the other half on the right shoulder. One test sample was taken at each bridge for determining the background concrete chloride level. Twelve two-inch diameter cores were taken at two of the magnesium chloride test sites.

1.5.2 Laboratory Testing

The laboratory testing involved measuring the twenty chloride contents for each bridge deck. A total of 400 test samples were tested. The test method AASHTO T-260, an acid soluble method, was used. A testing laboratory with well qualified and experience staff performed the laboratory test portion of the work.

1.6 DATA REFINEMENT

1.6.1 Remove Background Chloride Levels

One chloride content at each site was taken at the 4 in. (102 mm) depth for a background chloride reading, to be subtracted from all test data on that bridge. Free chlorides were found at that level so calculations were done to determine the actual background levels, which were found to average 0.27 lb/yd^3 (0.16 kg/m^3) for the twenty bridges.

1.6.2 Remove Outliers

Outliers are data points that are so far outside of the normal trends that they are identified as being erroneous. The error could result from many causes in the field or laboratory portions of the work. Outliers are removed prior to analysis to improve accuracy. One outlier was found out of the 400 data points.

1.7 DATA ANALYSIS

This stage involved rigorous data analysis for findings.

1.7.1 Statistical Analysis and Hypothesis Testing

Standard statistical analysis procedures were used to determine the adequacy of the data and validate hypotheses. The data was analyzed for trends and findings. Questions were formulated on the effects of the type of deicer on the chloride diffusion rate parameters of surface concentration and diffusion coefficient.

The chloride content in the wheel paths was much higher at all depths than the non-wheel paths. Significantly higher chloride contents were found at lower concrete depths on the bridges exposed to magnesium chloride. The diffusion coefficient for concrete exposed to magnesium chloride was significantly higher than for the sodium chloride only sites.

7.2.1 Findings

Among others, the data analysis showed the following:

- For all six sub-groups of test data the magnesium chloride bridges had higher chloride concentrations, but the difference was not statistically significant is some cases.

- There was a significant difference between the wheel path and non-wheel path chloride contents.

- Wheel path data averaged 243% higher than non-wheel path chloride data, regardless of whether magnesium or sodium chloride had been used.

- At the 1.5 in. (37.5mm) depth the chloride contents in the wheel paths on magnesium chloride-treated bridges were 78% higher than the control sodium chloride bridges.

- At 2.25 in. (56.3 mm) depth the chloride contents in the wheel paths on magnesium chloride-treated bridges averaged 185% higher those measured on the control sodium chloride bridges with a range from 48% to 321% higher.

In order to investigate the observed trend of increased rate of diffusion of magnesium chlorides, diffusion analysis was used to calculate diffusion coefficients for all twenty sites. Diffusion coefficients were calculated in several different manners using the two upper data points at each test location, using the top and bottom data points, and by averaging the two coefficients thus determined.

- The calculated chloride diffusion coefficients in the wheel paths on bridges exposed to magnesium chloride anti-icer from 1989 to 1998 averaged 120% (0.048 in.^{2}/year) higher than on bridges exposed to sodium chloride deicers from 1989 to 1998.

- The range in the difference was between 60% to 180% higher for bridge decks exposed to magnesium chloride anti-icer.

The measured and calculated diffusion parameters were used to determine the effect of magnesium chloride on the time to initiation of corrosion.

- The time to corrosion was found to average eleven years sooner for the magnesium chloride test sites than the control sites.

- The time to corrosion difference is greater when the cover depth difference is greater.

1.8 EFFECTIVENESS OF PREVIOUS MONTANA BRIDGE DECK REPAIRS

The general effectiveness of epoxy overlays and concrete deck overlays was reviewed by analyzing the chloride profiles of repairs done in 1993 to three bridges in the magnesium chloride portion of Interstate 90. Properly applied polymer overlays applied at the right

time usually add about fifteen years service life to bridge decks, while properly applied concrete overlays when applied at the right time usually add about thirty or more years to expected service life.

1.9 DISCUSSION OF SERVICE LIFE IMPACT FROM MAGNESIUM CHLORIDE

The condition of the wheel path area is critical to the service lives of bridges. The high wheel-path chloride content will reduce the service lives of bridges, since future wheel path damage cannot be ignored while damage to non-travel areas can often be ignored. The effect of magnesium chloride on typical bridge service lives was calculated using chloride diffusion analysis to compare the different times to corrosion in the resulting service life between application of magnesium chloride and sodium chloride deicers. The expected service lives of the two deicing scenarios were determined based on their respective times to corrosion for typical Montana decks. The reductions in service life are related to rebar cover depths and will vary from bridge to bridge. Overall, the impact on remaining bridge service life will be a reduction of 20 to 30%.

1.10 CONVENTIONAL DEICING CONTROL COST SCENARIO

The first step in finding the economic impact of magnesium chloride on bridges was to find the baseline bridge replacement costs of the reference scenario with conventional deicing. The normal service lives of bridges vary, depending on site conditions. The total bridge inventory was subdivided into three service life groups by the expected life under exposure to conventional chloride based deicers:

1. Heavily treated bridges, generally on the Interstate system, estimated to have average service lives of fifty years, ranging from 35 to 65, due to their high AADTs and allowable speeds, heavy truck traffic and deicer application.

2. Moderately treated non-Interstate bridges with traffic counts greater than 500 per day, estimated to average 65 years service life with a typical range from 45 to 85 years.

3. Non-treated bridges. Bridges with traffic counts less than 500 per day were estimated to average eighty years life and will never be exposed to deicers.

1.10.1 Future Bridge Replacements, Numbers, and Costs

The Montana bridge inventory database was used to determine the year of future replacement for all 4698 bridges based on their year of construction and the exposure category and life shown above. The number of bridge replacements per year under

conventional deicing was found and plotted. Using average unit cost data from MDT the replacement value of the total inventory was found to be $1,850M.

Most of the $710M investment in Category 1 bridges occurred between 1960 and 1980. With expected service lives of about fifty years, the oldest bridges of this group will begin needing replacement in about ten years. Replacement costs for this significant group of bridges will be quite high for the period of 2010 to 2030, regardless of whether magnesium chloride is used to increase the deterioration and replacement rates.

A large group of Montana bridges will never be deiced. The future costs of this group are not affected by bare pavement strategies and are not reflected in the cost analysis.

Using the replacement cost and year of each bridge, the total annual bridge replacement needs of future years was found for the control scenario of conventional deicing. Life cycle cost analysis was used to compare average costs over different time periods from twenty to sixty years into the future. Future bridge replacement costs are reported in two ways:

- In today's dollars with current replacement unit costs and converting future costs to current dollars with a 4% value of money
- In future dollars, neglecting the annual 4% loss in value of money and adding 2% to include increased future environmental, worker safety, and construction standards.

1.11 FINDING THE ECONOMIC IMPACT OF MAGNESIUM CHLORIDE

The economic impact from two possible pavement management scenarios was assessed:

- anti-icing practice limited to only those roads currently treated with magnesium chloride,
- anti-icing with magnesium chloride in place of conventional deicing practice on most of the Montana road system.

1.11.1 Limited Magnesium Chloride Use

At present MDT is only using magnesium chloride on a limited number of roads. The economic impact of switching from conventional deicing to limited use of magnesium chloride anti-icing was found by:

- identifying the bridges currently treated with magnesium chloride
- repeating the process described in section 10 using revised bridge service lives

The results are graphically expressed in numbers and costs of bridges replaced in future. The results are compared with the control scenario of conventional deicing, and the increased future bridge replacement costs resulting from use of magnesium chloride are expressed in current and future dollars.

1.11.2 Complete Switch to Magnesium Chloride

The second pavement management scenario is complete switch from conventional deicing to magnesium chloride anti-icing. The long-term bridge costs were found. The increase in costs from this scenario compared to the control scenario represents the economic impact. The results are graphically expressed in numbers and costs of future bridge replacements. The results were compared with the control scenario of conventional deicing and are expressed in both current and future dollars.

1.12 ECONOMIC IMPACT CONCLUSIONS

The economic impact on magnesium chloride use on Montana bridges will vary due to factors such as analysis period, numbers of bridges treated, amounts of anti-icer needed, site conditions, future cost of money, and effect on individual bridge service lives. The latter factor varies with individual bridge age, cover depth, and relative amounts of chemical being applied, which is something that will change over time. Sensitivity analysis was done with different future time periods and typical average conditions.

1.12.1 Limited Magnesium Chloride Use

Conservative estimates of the economic impact from continuing limited magnesium chloride use at bridge sites are based on 20% reduction in service life. They result in:

- An average annual increase of $2.2M in current dollars over the next 20 years
- a total increase of $33M in inflated future dollars over the next 20 years,

1.1.2.2 Complete Switch to Magnesium Chloride

Conservative estimates of the economic impact from complete switch to magnesium chloride use at bridge sites are based on 20% reduction in service life. They result in:

- Average annual increase of $10.9M in today's dollars over next 20 years
- a total increased cost of $270M in inflated future dollars over the next 20 years,

SECTION 2.0

SCOPE OF WORK

SECTION 2 SCOPE OF WORK

2.1 INTRODUCTION AND BACKGROUND

Montana Department of Transportation (MDT) has used road surface deicers for winter maintenance for over twenty years. During the past ten years new materials, including some anti-icing materials containing magnesium chloride, are being marketed and may be more effective than the traditional sodium chloride deicers. Anti-icing involves treatment of road surfaces prior to snowfall, whereas deicing involves treatment after. MDT has a product approval system in place to evaluate proposed anti-icing and deicing products on the basis of environmental and corrosion performance tests. The corrosion test applies to exposed steel and does not address corrosion in reinforced concrete, where chloride ions depassivate the steel. Chloride-based deicers are potentially destructive to concrete bridges. This study involves the field testing of twenty bridges, ten exposed to sodium chloride deicer and another ten exposed to magnesium chloride anti-icers during the past ten years. The purpose of the work was to investigate the longterm economic implications on the bridge infrastructure of using magnesium chloride-based anti-icer in place of conventional deicers.

2.2 SCOPE OF WORK

In September of 1998, Reid Crowther & Partners Ltd. (RCPL) submitted an unsolicited proposal to MDT to assess the economic impact of using magnesium chloride deicers on the MDT bridge infrastructure, currently valued at about $1,850,000,000. The proposal allowed some flexibility for RCPL to refine the scope of work during the course of the project. Eventually, the scope of work included the following tasks:

1. Review the state of the art of chloride ion diffusion through concrete,
2. Investigate MDT's practices and history on use of magnesium chloride anti-icers, identify areas where magnesium chloride is being used,
3. Work with MDT in the selection of appropriate bridges sites for comparing the corrosion effects of magnesium chloride anti-icers versus sodium chloride deicers,
4. Develop sampling procedures to collect appropriate and representative test data at various depths,

5. Provide qualified traffic control, personnel and equipment for taking test samples at the twenty sites,

6. Select and oversee a qualified testing laboratory to conduct chloride content tests using the AASHTO T260-84 test method,

7. Perform statistical analysis on the chloride test data to validate its reliability,

8. Analyze the data for possible differences in the chloride ion absorption and diffusion rates of bridges treated with the two deicing materials,

9. Use the differences in chloride diffusion rate to determine the differences in the time to corrosion of typical MDT reinforced concrete bridge components for the two materials,

10. Quantify the differences of the two materials on the service lives of typical Montana bridges,

11. Assess the differences resulting from the use of magnesium chloride on typical Montana bridge long term rehabilitation and replacement costs,

12. Extrapolate the long term cost differences to two scenarios, first considering only the Montana bridges currently being treated with magnesium chloride anti-icers, and secondly considering the theoretical costs if all heavily travelled roads in the state were treated thusly,

13. Report the findings and recommendations.

SECTION 3.0

PROJECT METHODOLOGY

SECTION 3 PROJECT METHODOLOGY

The project goal was to quantify the potential long-term costs to Montana bridges related to possible switching from conventional deicing practice to magnesium chloride anti-icing. Two possible pavement/bridge management scenarios were analyzed:

1. If current practice of doing magnesium chloride-based anti-icing on a small portion of the bridge system is continued.
2. If conventional practice is replaced with magnesium chloride anti-icing policy is extended to the entire road system likely to require such treatment in the future.

The two management scenarios were compared economically, based on future bridge replacement costs, with the baseline scenario of only using conventional deicing with sodium chloride based products.

3.1 OVERVIEW OF PROJECT METHODOLOGY

The project methodology can be summarized in the following steps:

- Review the state of the art on chloride diffusion.
- Select two similar groups of bridges, one subjected to conventional deicing practice and the second subjected to anti-icing practice with magnesium chloride products.
- Accurately collect chloride content test data from the two groups of bridges on I-90.
- Establish the baseline chloride parameters for typical conventionally deiced bridges.
- Use field test data to compare the effect of magnesium chloride versus sodium chloride on diffusion parameters of surface chloride content and diffusion coefficient.
- Use statistical analysis methods to confirm the adequacy of the data for use in further calculations.
- Use chloride diffusion analysis to find the compare the effect of magnesium chloride versus sodium chloride on remaining bridge service lives.

- Analyze the ages and replacement values of Montana bridges if current deicing policy is continued. Categorize the expected bridge service lives by their chloride exposure conditions, recognizing that some bridges will never be exposed to de-icing.
- Considering the ages of the individual bridges and their general chloride exposure conditions, predict the future replacement years for each bridge in the system.
- From the estimated bridge replacement years find the baseline annual bridge management costs for Montana bridges if exposed to conventional deicers. These costs will be related to both replacement and rehabilitation/repair activities.
- Adjust the future bridge replacement years to include the corrosion effects of magnesium chloride and re-calculate the bridge system long-term management costs.
- Consider the time effect on the value of money. Use life cycle cost analysis to analyze and sum the long-term annual bridge replacement costs of conventional deicing versus magnesium chloride anti-icing in two scenarios: current practice of treating only certain roads with magnesium chloride and theoretical treatment of entire bridge system. The annual economic impact is the difference between the life cycle costs for conventional deicing versus magnesium chloride deicing.

3.2 PROJECT DESIGN CONSIDERATIONS

Conventional deicing practice has been evolving in Montana for over twenty years and is expected to continue to change in the future. MDT data on the amounts of ice-treating chemicals used in the past ten years show a continuous upward trend, and this trend is similar to that reported by other bridge jurisdictions. This trend is related to some other general trends, which include:

- Increases in highway AADTs,
- Increases in the level of service demanded by the traveling public,
- Increases in speed limits.

This study is complicated by the fact that it analyzes future conditions that are not entirely known. The study compares the long-term economic consequences of continuing with an evolving conventional deicing practice versus switching to a new and possibly more cost-efficient policy of anti-icing. To some extent the work requires shooting at a moving target, since both practices may become more efficient in the future.

3.2.1 Real World versus Laboratory Studies

Both field and laboratory studies have advantages and disadvantages. Pure laboratory studies control most of the performance variables, but they often create artificial conditions that accelerate the aging process in order to more quickly reach conclusions. Real world studies may be done in natural conditions with longer time frames, but with the lack of control of many variables. This project did not involve laboratory research, where all but one performance influencing variable was controlled prior to and during the data collection period. The project is based on the findings of real bridges exposed for long periods of time to real world conditions. For better accuracy, field studies should involve a sufficient amount of data to offset the variability caused by a higher number of uncontrolled variables.

3.2.1.1 Advantages of Real World Bridge Studies

The general advantages of doing this study with real bridge test data are several. First, although the actual amounts of deicing chemicals applied were unknown, the work involved ten years of exposure time to a variety of climatic conditions with some winters being harsher than others. Over the ten-year period the variations in application rate due to climate even out. Another advantage of field-testing is that it involves bridges exposed to real conditions as opposed to unrealistic laboratory conditions intended to control certain variables. The deicer application was done by real people using real equipment and practices, rather than laboratory simulations. The concrete used in this study was mature real world concrete, rather than green laboratory concrete. The concrete tested in this study should be similar to what exists in the Montana bridge system if magnesium chloride deicer will now be regularly applied.

3.2.1.2 Reducing the Site Variables

Proper site selection can reduce the number of performance influencing variables. The site selection process of this project attempted to reduce the number of uncontrolled variables influencing chloride ingress by the conscious selection of bridges where many of the variables were similar. This practice was done partly by identifying highway sections where the bridges had been deiced using consistent equipment and practices. Another consideration was the selection of test bridges on Interstate sections where the bridges had generally been constructed in the same time period, using similar standards of construction, and similar concrete materials with similar durability properties.

MDT's staff is subdivided into districts, where the maintenance policies are generally consistent as long as the responsible staff does not change. Various members of MDT's staff provided input to RCPL's understanding of deicing practices.

3.2.2 Test Site Selection Process

A group of test sites with a known history of deicing materials and practices was desired. Necessary information included the approximate year when deicing was begun, since time is a major factor in calculations with Fick's Second Law of Diffusion.

3.2.2.1 Initial Approach to Test Site Selection

The methodology of the project required testing bridges that had been primarily exposed to either magnesium or sodium chloride deicers for relatively long periods of time. Sodium chloride test sites were relatively easy to find, having been used for a longer period, since the late 1970's. Magnesium chloride was introduced in certain areas in the late 1980's and therefore test sites were more limited. It was considered important to identify sites where there was reasonable knowledge of the history of which products were used. It was equally important to eliminate the effects of as many other test variables as possible.

One approach would have been to test recently replaced decks or recently constructed overlays. An investigation of the locations of recent overlays and deck replacements showed that there were few such sites suitable for the test program due to the following reasons:

- There was a general lack of reliable information on the deicing history of individual bridges,
- While bridge deck concrete overlays were newer and more likely to have known deicing histories, most prospective overlay sites were too new to have absorbed sufficient chlorides for accurate calculation of diffusion parameters,
- Due to the relative newness of magnesium chloride usage, very few bridge decks had been exposed to magnesium chloride for long periods.
- Excessive differences in the site exposure conditions and other test variables associated with chloride diffusion and deicing practices,
- Significant differences in design and construction standards.

3.2.2.2 Test Site Selection Criteria

As deicing practice has evolved in Montana, some roads have much longer histories of conventional deicing than others. Future use will likely continue to increase. In order to predict the future chloride exposure conditions of many bridges that are not currently

being deiced, it was necessary to measure the chloride ingress parameters of bridges with a known history of chloride exposure.

The final site selection included the following criteria, among others:

- traffic safety, one way bridges with good clear sight distance preferred,
- representative or typical nature of the bridges, their design and condition,
- length of time exposed to magnesium chloride,

The test site selection process involved finding a group of similar bridges exposed to similar weather and traffic conditions where magnesium chloride had been used for a long time and then to compare test data with that from another group of similar bridges exposed only to conventional deicers. Such a group existed near Missoula.

A 60-mile portion of Interstate 90 west of Missoula was identified for possible use. Half of this section of road, about 30 miles, was in the Saltese District and had experienced magnesium chloride deicer for the past ten years. The other 30-mile section in the Superior District had primarily been exposed to sodium chloride deicer. The bridges had been constructed during the period of 1960 to 1984 of reasonably similar construction standards and materials. The bridges were between five and 30 years old when they were first exposed to magnesium chloride. Both the magnesium chloride and conventionally deiced section of road had the same composition of older versus newer bridges. The traffic volumes and other site conditions influencing the amounts of deicers used were similar for both sections. Being in the same geographic area, the overall weather conditions during the ten-year period were reasonably the same. By involving a group of data from ten bridges exposed to each of the two deicers, the individual differences in concrete permeability, amount of deicer applied, tendency for differential surface icing, and other variables would balance out. Prior to final selection the entire group of potential test sites was inspected to eliminate from testing any of the less than desirable candidates.

Several repaired sites were also included in the test group. Two bridges that had received thin polymer overlays in 1993 were tested, as well as one bridge that had been repaired with a latex modified concrete overlay in 1993. The purpose of including these sites was to assess the performance of the repairs in extending the service life of the decks.

3.3 TEST METHODS

The work of this study required that accurate sampling and testing procedures be used. Considerable care was taken to ensure that qualified staff was involved in both the site sampling and laboratory testing stages of the work. The state of the art of chloride testing was first reviewed to ensure that proper procedures were used for both field and laboratory testing. Various experts were consulted to discuss proposed test procedures.

3.3.1 Field Sampling

3.3.1.1 Safety

Traffic safety during field testing was a primary concern. The field sampling involved first establishing safe conditions. All test sites involved similar one-way traffic conditions for consistency of traffic control methods. Qualified personnel inspected the sixty-mile highway section several weeks prior to beginning testing. Safety items, such as clear sight distance from nearest curve to the bridge, were recorded for consideration prior to finalizing the actual test sites. Bridges with the greatest clear sight approach distances were preferred. Traffic was diverted into the left lanes and testing was confined to the right sides of the decks. An approved local Missoula contractor supplied traffic control during the work. Due to the field testing methodology, no significant traffic disruption was experienced during the work.

3.3.1.2 Test Locations

Traffic was directed onto the left lane to allow working on the right wheel path and right shoulder of the decks. The decks were first chain dragged to identify possible delaminated areas, and sound, representative areas were selected for testing with avoidance of the following:

- surface cracks,
- delaminations,
- surface scaling,
- other types of visible damage.

Cover depths were measured using an accurate pachometer at forty to sixty locations on each bridge, depending on the size of the bridge. The accuracy of the pachometer was determined to be within 1/8 inch (3 mm) from comparison with measurements of core samples from non-Montana bridges.

A template approach was used to determine the approximate individual test locations. The actual test locations were then adjusted at the site to avoid cracks, surface popouts, or other defects that would affect chloride diffusion rates.

3.3.1.3 Sampling in Wheel Path versus Non-Wheel Path Locations

Since Montana roads are subjected to studded snow tires, and the effect on chloride absorption was unknown, data was taken in both wheel path and non-wheel path areas. The test location template required half the samples to be taken from the right wheel path and the other half from the right shoulder area outside the wheel path.

3.3.1.4 Sampling Procedures

Four hundred powder concrete samples were extracted from the twenty bridge test sites. A 1¼ in (31-mm) diameter drill bit was used to pulverize samples for extraction. The sample depths are measured within an accuracy of 1/8 in (3 mm). The extraction work was done by experienced personnel using care to prevent contamination between powders from different depths. The test holes and drill bits were continuously cleaned with compressed air between drilling operations.

3.3.2 Laboratory Chloride Content Testing

Although cheaper than titration testing, the new SHRP rapid chloride test method was ruled out for use in this project due to its lack of accuracy. Instead, the AASHTO Method T-260 (Acid Soluble Test Method) was used. The method involves extraction of chlorides with hot nitric acid, filtration, and potentiometric titration. It was thought that acid soluble testing would be more accurate than water soluble test methods. Duplicate tests were performed on every tenth sample and these results were reported for comparison of accuracy. The duplicate results were generally within 3.5% of the original tests. Reference standards were run after every set of twenty test samples.

3.3.2.1 Laboratory Qualifications

The laboratory work involved testing 400 concrete powder samples for chloride content. Accuracy was foremost of our concerns. Proposals were solicited from several qualified testing laboratories to perform the titration tests for chloride content. Information was requested concerning quality control procedures and appropriate staff expertise. The laboratory test work was awarded to Levelton Engineering Ltd. on the basis of their having the most qualified staff and procedures to do the work.

3.4 DATA ANALYSIS

The data analysis work involved the following tasks:

- Determine background chloride levels (chemically combined chlorides not available to promote corrosion)
- Adjust test data by subtracting chloride background contents
- Identify and remove bad data, outliers (1 removed)
- Exploratory data analysis for possible trends
- Hypothesis testing of observed parameters and data trends
- Statistical analysis for validation of hypotheses
- Compare absorption rates of magnesium and sodium chlorides in concrete
- Calculate diffusion rates for all sites using chloride diffusion analysis
- Compare diffusion rates of magnesium and sodium chlorides in concrete
- Categorize Montana bridge inventory according to expected service life
- Use inventory data on bridge construction year and exposure types to estimate inventory projected bridge replacement years and costs with conventional deicer
- Use typical Montana deck reinforcing steel cover depths, measured chloride diffusion parameters, and Fick's Law to determine the ranges in the times to initiation of corrosion (service life) for typical bridges and exposure categories
- Use chloride diffusion analysis to compare the times to initiation of corrosion (service life) for typical bridges exposed to magnesium and sodium chloride
- Analyze the range of impact of magnesium chloride on typical bridge service lives
- Apply the service life findings on the entire inventory
- As an aside to the main project goal, use chloride test data to quantify the effect (success) of some Montana bridge deck repairs on service life

3.5 EFFECT OF MAGNESIUM CHLORIDE ON BRIDGE SERVICE LIFE

For bridges subjected to chlorides the bridge service life curve typically consists of three (3) general stages:

- 1. Chloride diffusion,
- 2. Reinforcing steel corrosion and
- 3. Structural deterioration and damage.

Since the effect of increased numbers of chloride ions would primarily impact the diffusion stage, the effect of magnesium chloride on chloride ion diffusion rate was investigated. This assumption is conservative, since increased chloride content may also reduce the electrical resistivity of concrete, thereby accelerating the corrosion rate and the damage growth rate, thus affecting the other two service life stages.

3.5.1 Effect on Time to Initiation of Reinforcing Steel Corrosion

Using the results of the chloride diffusion analysis described in the previous section, further chloride diffusion analysis was used to compare the time to corrosion for the two types of deicers. An average surface chloride concentration and a range of depths were used to determine the time to corrosion for each bridge type versus reinforcing steel depth. The results were then compared to determine the difference in time to corrosion for the two bridge types.

3.6 BRIDGE INVENTORY VALUE AND LONG TERM MANAGEMENT COSTS

The project methodology involved comparing the life cycle costs of maintaining the MDT bridge infrastructure with the previous de-icing policy with an alternative policy of anti-icing with magnesium chloride. The difference in the two costs would be the economic impact resulting from the new policy.

3.6.1 Baseline Bridge Replacement Costs

In order to find the economic impact of switching to magnesium chloride, the currently required bridge replacement costs were needed for comparison purposes. The inventory was subdivided into exposure class categories, on which service life would be based. Assumptions of typical average bridge service life were made for each category. Although the assumptions may not be entirely accurate, since the goal was to determine the difference in the bridge replacement costs for magnesium chloride versus sodium chloride, any error in the assumptions would likely cancel out. The first step involved an

analysis of the bridge inventory to determine the expected deicing requirements and the resulting service lives if conventional deicers were continued to be used.

3.6.1.1 Analysis of Montana Bridge Inventory

Montana roadway classifications are defined in MCA 60-2-125. The seven classifications are Interstate, National Highway System, primary, secondary, urban, state highway, and local roads.

The bridge inventory database obtained from MDT in fall of 1998 showed a total of 4,698 existing bridges on all types of Montana roads. Depending on the severity of exposure conditions, size, location, as well as other design and construction factors, these bridges will have wide ranging service lives. Some will last much longer than others. Many of the bridges are on lightly traveled roads that are never deiced, and their long service lives reflect this benign environment. At the other service life extreme are the Interstate bridges, which carry heavier loads, higher traffic, and are exposed to higher amounts of road deicing chemicals. The most important easily measured factor in estimating future service life is the average daily traffic or ADT since many other significant factors such as amount of deicer used are related to ADT. ADT can vary significantly during the lives of some bridges due to development. In contrast, the traffic count on Interstate bridges generally stays high and the traffic count on local road bridges generally stays low during the course of the bridge's life.

For the purposes of cost analysis simplicity, the bridge inventory was subdivided into the following three categories according to average expected bridge service life.

Table 3-1 Expected Bridge Service Life with Conventional Deicers

Bridge Exposure Category	Typical AADT (vehicles per day)	Amount of Deicing Chemicals Applied	Estimated Average Service Life (Years)
1	2,500-10,000	Heavy	50
2	500 to 2,499	Moderate	65
3	100 to 499	None	80

The future bridge replacement years for all individual bridges in the state were predicted based on the average bridge service lives outlined in the above chart. The replacement

values were calculated for individual and total bridges in each of the bridge exposure categories using an average unit replacement value of $108/ft^2 ($1150/m^2) by bridge deck area. The estimated unit cost includes all costs of replacement, engineering, demolition, reconstruction, and detours. Greater explanation, charts, and graphs are included in Section 10 and Appendix C.

3.6.1.2 Annual Bridge Replacement Costs

Once the future bridge replacement costs for the entire inventory were determined, they were sub-totaled as annual bridge replacement budgets for the purpose of comparison with alternative bare-pavement scenarios.

3.6.1.3 Effect of Magnesium Chloride on Bridge Service Life

Using the relationship between time to corrosion and reinforcing steel depth for the two bare-pavement management types, as described in Section 3.5, the difference in time to corrosion for a typical reinforcing steel depth was determined. Using this difference and the bridge service lives for different categories, the variations in impact to bridge service life were determined. The variables influencing the range of impact are discussed.

Data analysis on the twenty I-90 bridges found that the chloride diffusion rate in bridge wheel paths exposed to magnesium chloride was significantly higher than of bridges exposed to sodium chloride. Significantly higher chloride levels were found at deeper concrete depths for the magnesium chloride treated bridges in the Saltese District. Use of magnesium chloride was found to decrease the time to corrosion of the decks, resulting in decreased bridge service lives.

3.7 LONG TERM IMPACT OF ANTI-ICING WITH MAGNESIUM CHLORIDE

3.7.1 Life Cycle Cost Analysis

Life cycle cost analysis or present worth analysis is an analysis method that involves a comparison of costs for various methods of managing the bridge inventory. The main goal of present worth analysis is to determine the most cost-effective management option in the selected analysis period and quantify the amount of savings. In this case present worth analysis was used to determine the economic impact of replacing sodium chloride with magnesium chloride deicer.

The cost analysis methodology is described in greater detail in Section 10.2.

3.7.1.1 Assumptions

- All future expenditures are converted into current dollars.
- The value of money over time is 4%.

Assuming the bridge service life is reduced by 25% when $MgCl_2$ anti-icer is used, the typical impact is summarized by the bridge service life estimates in table 3-2.

Table 3-2 Expected Bridge Service Life with $MgCl_2$ Anti-icers

Bridge Exposure Category	Typical AADT (vehicles per day)	Amount of Deicing Chemicals Applied	Estimated Average Service Life (Years)
1	2,500-10,000	Heavy	40
2	500 to 2,499	Moderate	52
3	100 to 499	None	80

3.7.2 Other Assumptions and Constraints

- 20 and 60 year periods were analyzed.
- Structures may be replaced more than once in the analysis period.

Due to the fact that the economic impact involves future replacement costs and budgets, life cycle cost analysis was used to convert future costs to today's dollars for comparative purposes in assessing the economic impact on inventory management.

The economic impact is not a fixed number, but will depend on some varying factors. Sensitivity analysis was done on these factors to show the ranges in future economic impact and increase in required annual future budgets due to use of magnesium chloride deicers.

SECTION 4.0

BACKGROUND INFORMATION

SECTION 4 BACKGROUND INFORMATION

This section describes background material relevant to the subsequent analysis of the effects of magnesium chloride on the times-to-corrosion, service lives, and resulting costs to Montana bridges.

4.1 REINFORCING STEEL CORROSION IN CONCRETE

Reinforcing steel corrosion in bridges has been documented in thousands of technical and articles during the past forty years. The primary mechanism of reinforced concrete corrosion in North America is ingress of chloride ions, whereas in Europe a substantial amount of corrosion is initiated by carbonation. The mechanism of chloride induced corrosion is complicated. Chloride ions penetrate concrete and depassivate embedded steel to initiate corrosion. Corrosion involves an electro-chemical process in which several chemical reactions occur simultaneously at anodes and cathodes, while electrical current flows between anodes and cathodes, either through the reinforcing steel or the moist concrete.

4.1.1 Anodes and Cathodes

Four of the chemical oxidizing reactions that may occur at anodes include[1]:

1. $Fe^0 \rightarrow Fe^{++} + 2e^-$;
2. $Fe^{++} + 2Cl^- \rightarrow FeCl_2$;
3. $FeCl_2 + H_2O + OH^- \rightarrow Fe(OH)_2 + H^+ + + 2\ Cl^-$
4. $2\ Fe(OH)_2 + \frac{1}{2}\ O^- \rightarrow Fe_2O_3 + 2\ H_2O$

The several stages of iron have different colors ranging from orange to black. Electrons are liberated at the anode and flow to the cathode. Ionic flow occurs through the moist concrete, which becomes an electrolyte.

The following are common chemical reduction reactions that occur at the cathodes[2]:

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[1] Weyers, Prowell, Sprinkel, Vorster; Concrete Bridge Protection, Repair, and Rehabilitation Relative to Reinforcement Corrosion: A Methods Application Manual, SHRP-S-360; 268 pages, 1993.

[2] Baboian; Synergistic Effects of Acid Deposition and Road Salts on Corrosion; Corrosion Forms and Control for Infrastructure, ASTM publication STP 1137; page 20, 1992.

1. $\frac{1}{2} O_2 + H_2O + 2e^- \rightarrow 2OH^-$
2. $2H^+ + 2e^- \rightarrow H^2$ (hydrogen gas evolution)
3. $O_2 + 4 H^+ + 4 e^- \rightarrow 2 H_2O$ (acidic solutions)
4. $O_2 + 2 H_2O + 4e^- \rightarrow 4 OH^-$ (neutral solutions)

Each corrosion cell has an anode and a cathode. Rust stains can visually identify the anodes, while the cathodes are adjacent electrically connected areas of protected steel.

4.1.2 Corrosion Cells

Corrosion cells are like chemically powered batteries with the driving force resulting from the thermodynamic process of steel returning its iron component to the natural oxidized state[1]. A corrosion cell has an anode, corroding portion, and a cathode, protected portion. A partial current flow occurs through the steel connecting the anode and cathode, while the electrical circuit is completed by ionic flow through the electrolyte, which is moist concrete. Stopping corrosion can be based on interfering with its electrical current flow or by interfering with the necessary chemical reactions.

Corrosion cells may be either macro-cells or micro-cells, depending on size. An example of a macro-cell would include portions of the top reinforcing steel mat in a bridge deck forming the anodes, while the entire bottom reinforcing steel mat, steel girders, or other electrically connected steel elements form the cathode, or protected areas. In this latter example the anodes are created by differences in chloride, moisture and oxygen contents in concrete surrounding the top reinforcing steel mat compared to concrete surrounding the bottom reinforcing steel mat.

Conversely, micro-cells are usually very small. They also result from the non-homogeneous nature of concrete. They often result from small concrete cracks intersecting at a 90° angle with steel reinforcing, thereby providing localized differences in oxygen, moisture, and chloride content.

The electrical current flow in a corrosion cell is in equilibrium between the anodic and cathodic chemical reactions. Many corrosion-mitigating products are based on the control of either the anodic or cathodic chemical reactions, which thereby control the overall electrical current flow. Examples are epoxy coated reinforcing, which controls the cathodic reactions, and corrosion inhibitors, which may control either the cathodic or anodic reactions.

4.1.3 Effect of Chlorides on Reinforced Concrete

Chloride ions are the most important single factor causing bridge deterioration in North America today. Free chloride ions exist in water solution and do not necessarily know from what source they came.

In non-chloride exposed reinforced concrete the highly alkaline concrete creates a passive condition for the reinforcing steel in which corrosion does not occur. The light surface oxide on the reinforcing steel is highly stable in this environment. When chlorides have penetrated in sufficient quantity to level of the reinforcing steel, the passive steel condition is destroyed and corrosion begins. Chloride corrosion threshold is defined as the chloride concentration needed to initiate corrosion. The typically accepted value for corrosion threshold is 1.2 lb/yd^3 or 0.71 kg/m^3. In reality, the corrosion threshold is not constant. It varies with factors such as the actual concrete's properties of hydroxide ion concentration, moisture content, oxygen content, and others[1].

The term 'time to corrosion' is the time required for sufficient chlorides to reach the steel components and initiate the corrosion process.

4.1.4 Rate of Steel Reinforcing Corrosion

The rate of corrosion is basically related to the electrical current flow resulting from the chemical reactions occurring at anodes and cathodes. Rate of corrosion is affected by many parameters such as temperature, chloride ion content[1], moisture content, dissolved oxygen content, electrical conductivity, the inverse of electrical resistivity, of the concrete, and others.

The electrical current flow is proportional to the numbers of iron atoms dissolving from the steel components and forming complexes with oxygen and hydroxides in the concrete. The rate of steel corrosion is directly proportional to the remaining service life of a steel reinforced structure.

4.1.5 Bridge Service Life

Bridge service life is defined as the time until a critical amount of damage has developed to require major rehabilitation or replacement. The damage is usually in the form of potholes resulting from the disintegration of corrosion induced concrete surface delaminations. The iron oxides and hydroxides that result from corrosion occupy more volume that the original iron atoms in the reinforcing. The increase in volume that accompanies corrosion results in potholing damage to bridge decks, as well as loss of steel section with accompanying reduction in load carrying capacity. Potholes present a

serious threat to public traffic, particularly on bridges in high speed locations, and especially when the potholes are located in the wheel paths.

4.1.5.1 Phases of Service Life

Chloride induced damage is the single major cause of bridge deterioration is North America. The service life curve is a plot of damage versus time. It consists of three phases, diffusion, corrosion, and damage. The diffusion phase is the time period before chlorides have reached the reinforcing steel in sufficient amounts to initiate corrosion. This does not happen uniformly due to variations in concrete cover depth, exposure conditions, and concrete permeability. The corrosion phase is the time period in which portions of the steel are corroding and building up pressure from the increased volume of the various forms of iron oxides. The damage phase begins when the corrosion induced pressure initiates cracking of concrete surrounding the reinforcing. The cracks propagate until they reach the concrete surface and potholes and visible damage can be seen. The damage phase ends when sufficient damage has occurred to end the bridge service life.

4.1.5.2 End of Service Life

In bridge decks the critical amount of deck surface damage needed to end service life has been found to be about 9 to 13% of the deck area in the most deteriorated traffic lane. Higher rates of steel corrosion equate with shorter remaining bridge deck service lives.

The chloride induced corrosion phenomenon is the major single cause of bridge replacement and rehabilitation in North America, resulting in a multi-billion dollar per year problem for bridge owners[3].

4.2 CHLORIDE DIFFUSION IN CONCRETE

4.2.1 Capillary System

Concrete consists of rock and sand cemented together by hydrated paste of cement and water. Concrete is generally a porous material, and as such it absorbs water continually from the environment. While the moisture level of the surface concrete continually fluctuates to maintain equilibrium with the atmospheric humidity, the interior of the concrete is always moist, typically over 80%[4]. The normal concrete capillary system provides relatively large channels for water and chloride solutions to penetrate and diffuse through. The interconnected capillaries may be ten to a thousand times the diameter of

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[3] Cady, Weyers; "Chloride Penetration and the Deterioration of Concrete Bridge Decks", Cement, concrete and Aggregates, Vol. 5, No. 2, page. 81, 1994.

[4] Weyers, Pyc, Sprinkel; "Estimating the Service Life of Epoxy Coated Reinforcing Steel"; American Concrete Institute Materials Journal, Vol. 95, No. 5, page 555, 1998.

water and chloride molecules. The capillaries are generally created by the passage of excess bleed water being squeezed out of fresh concrete prior to it setting. Other factors in capillary system development relate to the mix design, the aggregate gradation and proportions, and the amount of excess mix water beyond the relatively small amount needed for the hydration of cement. Over the years the bridge and structural design codes have changed, generally in the direction of reducing the water to cement (w/c) ratio by use of conventional and high range water reducing admixtures. Concrete constructed in the 1950's and 1960's generally had w/c ratios in the neighborhood of 0.5, whereas current practice often calls for w/c ratios of deicer exposed concrete as low as 0.35. The latter concrete is much less permeable due to the greatly reduced capillary system. Consequently, as the newer concrete mature they may become significantly less porous than concrete of previous eras.

Diffusion is a process of a fluid spreading or permeating through a permeable material such as soil or concrete. Fick's Second Law of Diffusion mathematically describes the process of chloride ion diffusion through concrete[1].

4.2.2 Fick's Second Law

Regardless of their source, chlorides migrate through concrete. Chloride migration in concrete is expressed by the equation below, where C is the chloride concentration at a depth, d, and a time, t. The abbreviation erf is for error function, a curve that can't be described by normal mathematical equations.

$$C_{d,t} = C_0\left[\left(1 - erf\,\frac{d}{2\sqrt{D_c \cdot t}}\right)\right]$$

The primary driving force in the diffusion process is the chloride concentration at the surface of the concrete, C_o, from which chlorides are being applied to the concrete. The concrete's property of resistance to chloride diffusion is expressed as the diffusion coefficient, D_c. The diffusion coefficient is a property related to the concrete's permeability property as well as the concrete's internal relative humidity or moisture content. The latter conditions are at least partly related to geographic location and annual climatic conditions. Concrete in coastal areas generally has higher diffusion coefficients than drier climates inland.

Fick's Second Law allows us to predict future changes in the chloride ion concentration at any depth from the concrete surface over any period of time if we know the particular concrete's diffusion properties of C_o and D_c.

Over a period of time of applying chloride ions, as in the process of deicing highways and bridges, the surface concentration of chlorides in concrete, C_o , gradually increases and approaches an upper limit with time. The upper limit is based on the amounts of chloride ions being applied. This chloride diffusion characteristic is shown later in this report. Over a period of time, the depth of chloride penetration as well as the chloride concentration at any depth from the application surface increases as shown conceptually in the figure below. The values shown in the figure were calculated for a specific combination of C_o = 10.2 lb/yd^3 (6 kg/m^3) and D_c.= 0.078 in^2/year (0.5 cm^2/year). For other combinations of C_o and D_c. the rate of penetration and chloride concentration buildup with time will be different, but the same general shape will occur as shown in the figure below.

Table 4 – 1 Chloride Penetration of Concrete With Time

	Time (years)										
Depth (inch)	1	2	3	4	5	6	7	8	9	10	11
0.40	3.50	3.90	4.40	4.60	4.75	4.86	4.94	5.01	5.06	5.11	5.15
0.80	0.68	1.57	2.16	2.56	2.88	3.10	3.30	3.44	3.58	3.69	3.79
1.20	0.06	0.40	0.81	1.18	1.48	1.74	1.96	2.16	2.33	2.48	2.60
1.60	0.01	0.08	0.24	0.45	0.65	0.85	1.05	1.23	1.39	1.54	1.67
2.00	0.00	0.01	0.05	0.13	0.25	0.36	0.50	0.63	0.76	0.88	1.00
2.40	0.00	0.00	0.01	0.03	0.08	0.15	0.22	0.29	0.38	0.46	0.55
2.80	0.00	0.00	0.00	0.01	0.02	0.04	0.08	0.12	0.17	0.22	0.28
3.20	0.00	0.00	0.00	0.00	0.01	0.01	0.02	0.04	0.07	0.10	0.13
3.60	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.02	0.03	0.04	0.06
4.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.01	0.02
4.40	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01
4.80	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
5.20	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
5.60	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
6.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

4.2.3 Factors in Rate of Chloride Diffusion

Major factors that relate to the rate of chloride diffusion in concrete include the following:

- time,
- temperature,
- climate and concrete moisture conditions,
- deck drainage characteristics
- concrete permeability
- surface abrasion wear, as by studded snow tires.

Note that the above factors were generally the same for the twenty-bridge test group used in this study.

By measuring chloride contents in concrete at different depths and using Fick's Second Law to calculate the essential diffusion parameters of C_0 and D_c we can predict future changes in chloride content with time. This allows one to predict remaining service lives of chloride exposed concrete, assess the effectiveness of bridge deck repairs, and assess the economic impact of alternative chloride-based deicers.

SECTION 5.0

PROPERTIES AND USAGE

SECTION 5 MAGNESIUM AND SODIUM CHLORIDE TREATMENTS

This section describes the chemical and physical properties of the two anti- or deicing materials, magnesium chloride and sodium chloride, and presents background information related to their field use.

5.1 CHEMISTRY OF MAGNESIUM AND SODIUM CHLORIDE

The following is a brief description of the basic chemical elements of magnesium, sodium and chlorine, as well as the compounds of magnesium and sodium chloride.

5.1.1 The Chemical Elements

5.1.1.1 Chlorine

The element chlorine was discovered in 1797. It occurs in nature in combined forms as common salt, sodium chloride, carnallite, and sylvite. In pure form it is a greenish yellow gas. Chlorine readily combines with most other elements. Chlorine is a very strong oxidizing agent, meaning it readily strips electrons from other atoms, especially metals. Chlorine is a stronger oxidizer than even oxygen.

5.1.1.2 Magnesium

Magnesium was first recognized as an element in 1755. It occurs abundantly in the earth's crust in combined form as magnesite, dolomite, and others. In pure form it is a light, silvery white, tough metal that is highly reactive. It does not occur in pure form in nature. It is highly flammable and burns or oxidizes with a blinding intensity.

5.1.1.3 Sodium

Sodium was first isolated in 1807. It is the sixth most abundant element found in the earth's crust, where it comprises 2.6%. It is highly chemically reactive and therefore is never found in pure form in nature. Sodium is most commonly found in nature as the chemical compound, sodium chloride or road salt. It also occurs as soda niter, cryolite, amphibole, zeolite, sodalite, as well as others. In pure form sodium is a dangerous, toxic, flammable, and explosive metal.

5.1.2 Chemically Combined Forms of Sodium, Magnesium, and Chlorine

5.1.2.1 Sodium Chloride

Sodium chloride can occur in liquid solution, example seawater, or it can be dried to a pure solid crystalline form, sometimes called rock salt or road salt. It is highly soluble in water and can exist in different concentrations, each with slightly varying properties of freezing point, specific gravity, viscosity, and such. In solution, sodium chloride readily ionizes. The sodium ions are positively charged, while the chloride ions are negatively charged. The ratio of sodium to chloride ions is one.

5.1.2.2 Magnesium Chloride

Magnesium chloride is similar to sodium chloride in that it occurs as a crystalline solid that is highly soluble in water. As the concentration of magnesium chloride changes, its melting point and other properties change as well. Magnesium chloride also ionizes in water solution to form positively charged magnesium ions and negatively charged chloride ions. The ratio of chloride ions to magnesium ions is two.

5.1.3 Significant Physical Properties

Some relevant properties of the above elements and compounds are presented in the table below.

Table 5-1 Properties of Chlorine, Magnesium, and Sodium

Name	Chlorine	Magnesium	Sodium	Sodium Chloride	Magnesium Chloride
Atomic numbers	17	12	11	N/A	N/A
Atomic weight	35.5	24.3	23.0	58.4	95.2
Melting Point (^oC)	-101	649	97.8	801	714
Boiling Point (^oC)	-34.6	1090	883	1413	1402
Molecular size in Angstrom (10^{-10} m)	3.6	1.6	2.0	5.7	8
Ionic Charge	-1	+2	+1	N/A	N/A
State	Gas	Solid metal	Solid metal	Solid Crystal	Solid Crystal
Density (g/cm^3)	3.17	1.74	0.97	2.18	2.32

5.1.3.1 Deliquescence and Hygroscopic Properties

Deliquescence is the property of a solid slowly dissolving by attracting moisture from the air. Hygroscopic behavior describes the property of attracting and retaining moisture. Both calcium and magnesium chloride are both deliquescent and hygroscopic materials. Calcium chloride is routinely used as a dust control material on unpaved roads, where its hygroscopic nature results in more sound road surface. Both calcium and magnesium chlorides are thought to retain moisture when they are absorbed in concrete. By keeping the concrete in a wetter condition they would decrease the electrical resistivity and increase the ionic flow needed to sustain the electro-chemical reactions involved in corrosion of embedded steel.

5.1.4 Diffusion Rates in Concrete

Concrete consists of rock and sand cemented together by hydrated cement paste. Concrete is generally a porous material, and as such it absorbs water continually from the environment. While the moisture level of the surface concrete continually fluctuates to maintain equilibrium with the atmospheric humidity, the interior of the concrete is always moist. The moisture makes it possible for ions such as sodium and magnesium to diffuse, since they exist only in liquid solutions in water. If the water was dried, as in an oven, the ions would re-crystallize or chemically react in some other way.

The table above shows sodium, chloride and magnesium ions to be approximately the same size, which is extremely small in comparison to the usual size of permeable voids in concrete. A relevant question is whether the two chemicals diffuse through concrete at similar rates. One reason why the ions might diffuse at different rates is their different tendencies to re-crystallize.

5.1.5 Deicing versus Anti-Icing

There are significant differences in the ways that magnesium and sodium chlorides are applied as applied as bare pavement-inducing treatments.

Traditionally, roads were sanded. Since sand contains water, the sand tends to freeze into lumps that do not easily pass through the hoppers in sanding trucks. Solid sodium chloride or road salt is added to the sand to prevent it from freezing into unmanageable lumps. Sand and rock salt (sodium chloride) were used primarily to attack existing ice on roads and bridges. This process became known as deicing.

On the other hand, a newer approach to bare pavement has been to prevent the formation of ice to road surface bond by applying the chemical before the ice exists. Properly done, this approach may be more cost-effective. The crucial factor in application is its timing.

This requires predicting the weather conditions, which is not easy. Improperly timed, the chemical may sit on the already iced surface or alternatively sit on the dry surface when the predicted snow doesn't occur. This approach is referred to as anti-icing.

Magnesium chloride anti-icers are supplied liquid forms with different concentrations of the active ice-melting ingredient. Normal magnesium chloride is a crystalline solid that can easily be dissolved in water solution at various concentrations. The freezing point depression effect of magnesium chloride depends on the resulting concentration of magnesium chloride. The typical concentrations used have been 30% by mass. Thirty percent by mass means that every ten pounds of liquid solution contains three pounds of solid magnesium chloride.

The initial concentration of either sodium or magnesium chloride changes after application to an icy or snowy roadway surface. As melting snow and ice dilute the concentration, the ice melting characteristics continually change. Both chemicals are applied in such concentrations that the subsequent ice melting abilities initially improve, reach a peak ice melting capacity, and then gradually decline with continued dilution.

The ability to effectively de-ice a roadway surface is more complicated than is often recognized. Effective deicing requires judgment of current temperature, subsequent temperature change, and amounts of snow and ice melted, among other things. Melting causes dilution, which affects the freezing point depression temperature. As most people would agree, predicting the weather is not easy. It is even more complicated in mountainous areas. Some concentrations of deicer can cause the roadway to become slipperier than no deicer. Deicing skill takes time to master. Liquid deicers, such as magnesium chloride, react differently with snow and ice than solid ones.

5.1.6 Benefits of Magnesium Chloride

In comparison to road salt, magnesium chloride is reported to be superior in the following respects:

- Faster snow and ice melting ability,
- Ability to melt snow and ice at lower temperatures,

It is only marginally more expensive than road salt.

5.2 USE OF ANTI-ICERS BY MDT

While detailed records are not available, MDT reportedly began deicing roadways in the late 1970's. The amount of chemicals used has tended to increase with time, speed

limits, public demands, and trends throughout North America to provide bare deiced pavement to the travelling public.

Winter maintenance is an important public service, as shown by the $10 million annual budget.

5.2.1 Amounts of Chemicals Used

Amounts of both liquid and solid chemicals used annually by MDT have been recorded since 1993. The table below shows the total amounts of both road salt and magnesium chloride purchased annually from 1993 to 1999. Note that the liquid deicers are expressed in US gallons of typically 30% by mass concentration, which have to be converted to an equivalent mass of solid deicer in order to allow an 'apples to apples' comparison.

Table 5.2 ANNUAL MDT CHEMICAL CONSUMPTION*

Year	Severity of Winter	Liquid Magnes. Chloride (x 1000 US gal)	Magnes Chloride Mass** ($x10^6$ lb)	Total Sand Used (x 1000 Cu. Yd.)	Sodium Chlor. Mass ($x10^6$ lb)	Total Chloride Used Mass ($x10^6$ lb)	Magnes. Chloride %Total Chloride Used	Sodium Chloride %Total Chloride Used
1993	Ave.	377	0.91	241	15.2	16.1	5.6%	94.4%
1994	Ave.	712	1.71	230	13.3	15.0	11.4%	88.6%
1995	Ave.	1,152	2.78	250	16.9	19.7	14.1%	85.9%
1996	Cold	1,687	4.06	307	21.3	25.4	16.0%	84.0%
1997	Cold	2,346	5.65	379	23.0	28.7	19.7%	80.3%
1998	Mild	1,743	4.20	365	20.9	25.1	16.7%	83.3%
1999	V mild	1,856	4.47	255	17.2	21.7	20.6%	79.4%

*Figures reported by MDT

**1 US gallon of 30% concentration magnesium chloride contains 2.41 pounds of crystalline magnesium chloride

From the above it can be seen that the total amount of chlorides being applied to the Montana bridge system have been increasing substantially over recent years. Even as the amount of liquid anti-icer has increased by leaps and bounds, the solid deicer has also steadily increased. When the effects of weather are taken into account, it is obvious that increasing amounts of deicers are being used. These increases will have an impact on the numbers of bridges developing chloride-induced deterioration problem as well as the severity of the problems.

5.2.1.1 Amounts of Chloride Ions in Sodium versus Magnesium Chloride

Sodium chloride molecules consist of one atom each of sodium and chloride. Magnesium chloride molecules contain two chlorides for each magnesium atom. In the table comparing the amount of salt used, the number are expressed in pounds of either salt. Actually, a pound of sodium chloride and a pound of magnesium chloride contain different amounts of chloride ions. The actual amounts of chlorides can be calculated using Avogadro's number, 6.023×10^{23}. One gram atom of sodium chloride weighs 58.4 grams and contains 6.023×10^{23} chloride atoms, weighing 35.5 grams. One gram atom of magnesium chloride weighs 95.2 grams and contains 12.046×10^{23} atoms of chloride weighing 71 grams. Therefore 60.8% of the mass of sodium chloride is chloride atoms, while 74.6% of the mass of magnesium chloride is chloride atoms. A pound of sodium chloride has 0.608 pounds of chlorides, while a pound of solid magnesium chloride has 0.746 pounds of chlorides.

Table 5.3 ANNUAL CHLORIDES FROM EACH CHEMICAL

Year	30% Liquid (US gallons)	Mass of Magnesium Chloride (pounds)	Chlorides from Liquid Mag Chloride (pounds)	Mass of Sodium Chloride (pounds)	Chlorides from Sodium Chloride (pounds)
1993	377,000	910,000	680,000	15,200,000	9,240,000
1994	712,000	1,710,000	1,280,000	13,300,000	8,090,000
1995	1,152,000	2,780,000	2,070,000	16,900,000	10,300,000
1996	1,687,000	4,060,000	3,030,000	21,300,000	13,000,000
1997	2,346,000	5,650,000	4,220,000	23,000,000	14,000,000

1998	1,743,000	4,200,000	3,140,000	20,900,000	12,700,000
1999	1,856,000	4,470,000	3,340,000	17,200,000	10,500,000

5.2.2 MDT Chemical Approval Process

MDT's concerns with deicers include impact to vehicles, bridges, storage and application. Previously salt was only used to prevent the sand from freezing. Over time, policies have changed and concerns now address issues such as dust and airborne pollutants.

MDT has approval standards in place for assessing new products. The standards include a series of requirements that evaluate environmental and corrosion characteristics of new products, including[1]:

- Tight limits on the content of eleven toxic metals,
- Corrosion requirements of National Association of Corrosion Engineers (NACE) Standard TM-01-69 (1976 rev.) as modified by Washington Department of Transportation (WSDOT) for deicer testing,
- pH limits, as per American Society of Testing Methods (ASTM) E 70
- For Deicer Category 1, minimum of 25% magnesium chloride
- Numerous other quality-control requirements.

Magnesium chloride costs about 20% more than sodium chloride[1]. MDT uses a best buy policy that combines the percentage of active ingredient with the bid price so as to compare "apples to apples". A recent modification to the policy includes the amount of corrosion test reduction in the price formula. MDT is concerned with the costs incurred by potential corrosion problems. They currently use corrosion-inhibited products. They work closely with other Pacific Northwest States (PNS) in setting standards for the deicer evaluation process. Independent testing is done by credible organizations such as HITEC, the Highway Innovative Technology Evaluation Center.

An example of a recently approved product is Ice Ban Plus, a 50:50 (50%) blend of Ice Ban and a 30% concentration of magnesium chloride solution. Ice Ban reportedly

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[1] Private communication with Dan Williams, MDT, 1998.

contains corrosion inhibitors. Ice Ban is acidic with a pH of about 2 and has a reported specific gravity of 1.28[2].

5.2.2.1 NACE Standard TM-01-69 (1976 rev.) Corrosion Test

The above corrosion test is part of the MDT and PNS approval requirements for deicers. This rigid test involves a 72-hour period of cyclic immersion of a standard steel coupon in the proposed deicing solution. A 3% concentration of the deicer is used and compared with a 3% reference solution of sodium chloride. The mass lost from the coupons due to corrosion is measured and compared. The required performance for approval is that the coupon mass loss in the deicer solution be a minimum 70% less than that in the reference salt solution.

Evaluation of the corrosion test method is outside the scope of this study, but the validity of this test would require equal amounts of dissolved oxygen in the two solutions. Corrosion rate stops without oxygen. The concentration of the proposed deicer appears less than the reference solution concentration. The test does not measure corrosion of embedded steel in concrete. The test does not consider the effect of time. Chlorides remain with time, but inhibitors are likely to break down. The corrosion test does not evaluate the life of the inhibitor, which may decompose over time while the chloride ions from the deicer cannot decompose.

For reinforced concrete to be protected by corrosion inhibitors, they would have to diffuse through concrete as fast as chloride ions in order to protect the steel. Organic inhibitors have relatively large molecules.

Another question is whether inhibited deicers would have any benefit when applied to decks that already contained chlorides. The nature of chloride diffusion is that as long as the surface chlorides are being continually replenished, whether by magnesium chloride or by sodium chloride, the driving force causing the deeper chlorides to continue diffusing toward the steel would still exist. If a deck had already been exposed to conventional chloride based deicers for twenty years, the chlorides would have a twenty year head start on the inhibitor molecules. The inhibitor would never reach the steel in time to be effective, unless its rate of diffusion were much greater than chloride diffusion. Thus, even if the inhibitors were shown to be effective on reinforced concrete, the use of inhibited deicers would likely have no benefit on previously deiced bridges.

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[2] Preliminary Evaluation Findings for Ice Ban™, CERF Report #40340, Highway Innovative Technology Evaluation Center, 1998.

5.2.2.2 Alternative Tests to Assess Deicer's Effect on Reinforced Concrete

It is possible that the current corrosion test method does not adequately measure the corrosion performance of new deicing materials in reinforced concrete and maybe not on exposed steel after long periods of time. Field-performance testing on real bridges may be more accurate methods of assessing the corrosion performance of new deicers. A quicker and more appropriate accelerated corrosion test method may be a Wiss, Janney, Elstner-type time-to-corrosion test method. In this test the proposed deicing products would be cyclically applied to standard reinforced concrete test specimens of constant permeability and cover depths, while monitoring the induced corrosion using electrical test methods such as copper sulfate electrode or linear polarization.

5.2.3 Interstate 90 Test Sections

The bridge test sites involved in this study are located on Interstate 90 west of Missoula. All sites are within a sixty miles section of divided highway between mileposts 0 and 61.8. Milepost 0 is at the Idaho border. The Saltese District of MDT provides maintenance of the highway between mileposts 0 to 33.5, while the Superior District of MDT maintains the next 28 miles of highway to the east. The Saltese District began using magnesium chloride on an experimental basis in about 1989, while the Superior District has had very sparse usage of the product during the past two mild winters.

SECTION 6.0

TESTING METHODOLOGY

SECTION 6 CHLORIDE TESTING METHODOLOGY

The field portion of this study involved collecting chloride test data from the concrete bridge decks for use in data and statistical analysis. The testing methodology was the same for all bridges, regardless of their deicing history. The data collection methods are described in the following sections.

6.1 DESCRIPTION OF FIELD SAMPLING METHODOLOGY

The first step in the process involved collecting representative powder concrete samples from the twenty bridges to be tested in the laboratory for chloride content.

6.1.1 Traffic Control Safety

Worker and public safety were top priorities in the field portion of this study. An experienced Montana firm, Alpine Construction, provided traffic control in conformance with the safety regulations of MDT for the purpose of creating a safe work zone with minimal disruption to the public.

Interstate 90 is a divided highway with two lanes in each direction. The right, or truck, lane was closed to traffic prior beginning testing. The lane was closed using approved methods consisting of “candle-cone” type delineators, several construction signs, and a gas powered arrow board. The bridges were tested on one direction of highway at a time to reduce the risk of accidents. Testing began on the most easterly bridge on the westbound direction, and the work proceeded in a westerly direction. After the last westbound deck was tested the crew changed directions and proceeded to test bridges on the eastbound lanes.

The traffic control crew had sufficient signage, manpower, and equipment to close two bridge sites at once. They prepared the next work zone while the testing crew was finishing their work on the previous site. This leapfrog technique for traffic control was used to increase work efficiency by reducing waiting time for traffic control to be set up at the next bridge test site.

6.1.2 Preparation for Testing

After closing the right lane of each deck to traffic, the testing crew measured the deck dimensions. The crew then marked a 4-ft. by 4-ft. (1.2 m x 1.2 m) grid on the closed deck lane. The grid is used to reference test locations on a plan view of each deck.

6.1.3 Chloride Test Locations

Accuracy in taking the chloride content test samples was an important aspect of the data collection phase of the project. Test locations were initially establish using a template, but final locations met the following criteria:

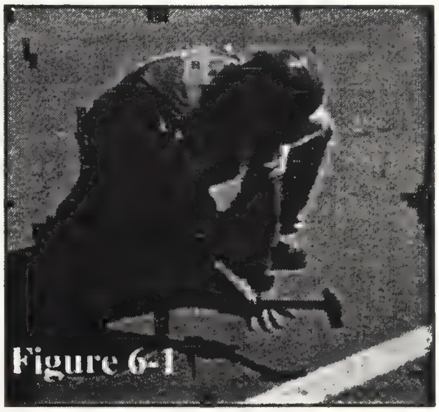


Figure 6-1

- The concrete deck/overlay was sound and of similar condition to the surrounding concrete
- The concrete was free of cracks
- The concrete was not delaminated. Hammer-sounding was done as shown in Figure 6-1
- If the site involved a thin polymer wearing surface, it was not debonded at the test locations

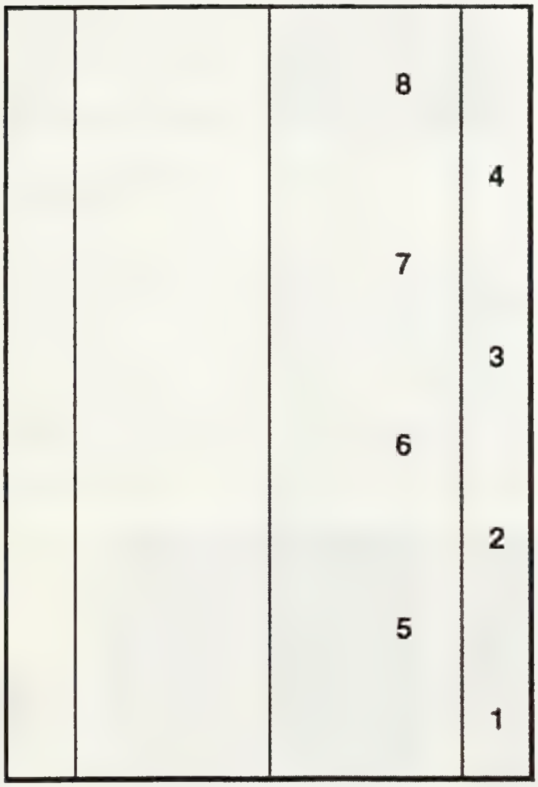
Initially, representative test locations were marked on the plan view of the deck in the same basic pattern for each site. Four test locations were in the roadway shoulder and four more were in the right lane, right wheel path.

The pulverized concrete powder samples were taken at several depths as shown in Table 6-1. The ranges refer to the test sample depth from the surface.

Table 6-1 Chloride Content Test Depths

Number	Depth Range inch (mm)	Nominal Depth inch (mm)
1	0.25-0.75 (6-19)	**0.50 (13)**
2	1.25-1.75 (31-44)	**1.50 (38)**
3	2.00-2.50 (51-63)	**2.25 (56)**
4	3.75-4.25 (94-106)	**4.00 (102)**

Test samples were not obtained from every depth at every test location. The typical pattern of the test locations is outlined in Figure 6-2.



Location Number	Nominal Sample Depths (inches)			
1	0.50			
2	0.50	1.50	2.25	
3	0.50	1.50	2.25	
4	0.50	1.50		
5	0.50	1.50	2.25	
6	0.50	1.50	2.25	4.00
7	0.50	1.50	2.25	
8	0.50			

- Test Locations 1-4 are in the right shoulder.

- Test Locations 5-8 are in the right (passenger) wheel path.

Typical Chloride Sample Locations and Depths at Each Location

Figure 6-2

Samples were taken as follows:

- Eight test samples at 0.50 in. (12.5 mm) nominal depth,
- six test samples at 1.50 in. (37.5 mm) nominal depth,
- five test samples at 2.25 in. (57 mm) nominal depth,
- and one test sample at 4.00 in. (102 mm) nominal depth.

The surface depths were selected to allow calculation of the rate at which chlorides have been diffusing into the deck. The 4 in. (102 mm) depth provide the background chloride content, the amount of chlorides that were in the concrete deck from the time of construction. Background chlorides may typically originate from the mixing water, the aggregates, or the admixtures used in the concrete mix. Accurate data analysis requires separating the externally applied chlorides from the initial internal chlorides.

Half the test samples were taken from the right wheel path and the other half from the right shoulder. Montana allows vehicles to have studded snow tires, which cause abrasive deck wear in the wheel paths. It was postulated that extra wheel path wear and/or tire pressure might result in higher or different chloride contents in wheel paths as opposed to non-wheel path locations.

6.1.4 Sampling Method

Chloride content laboratory tests involve pulverized concrete powder samples. Drilling into the deck with a 1¼" (31 mm) diameter drill bit creates the powder sample. The large diameter bit increases the volume of powder, reducing the spread in sample depth, and increasing the accuracy of subsequent analysis. A steel rod was loosely attached parallel to the drill bit to allow accurate measuring of the test sample depths. The exposed length of rod is monitored during drilling. The rod grows in length as the drill penetrates the deck as shown in Figures 6-3 and 6-4 above.

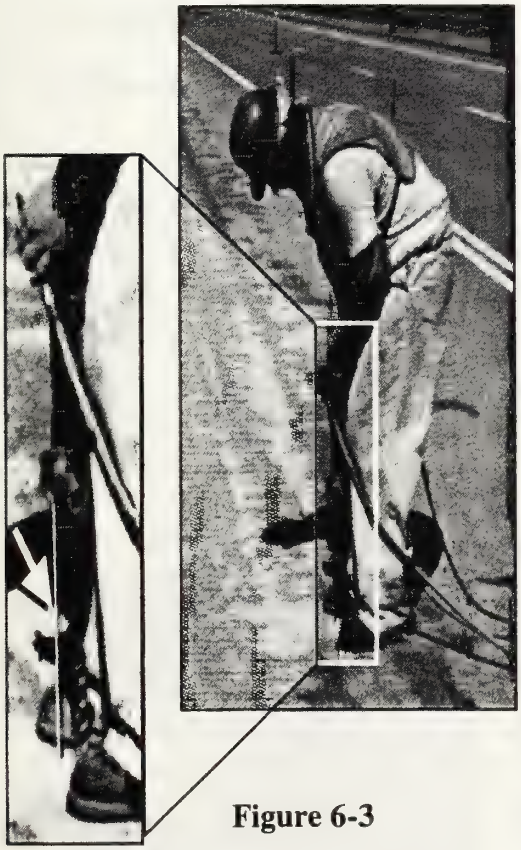


Figure 6-3

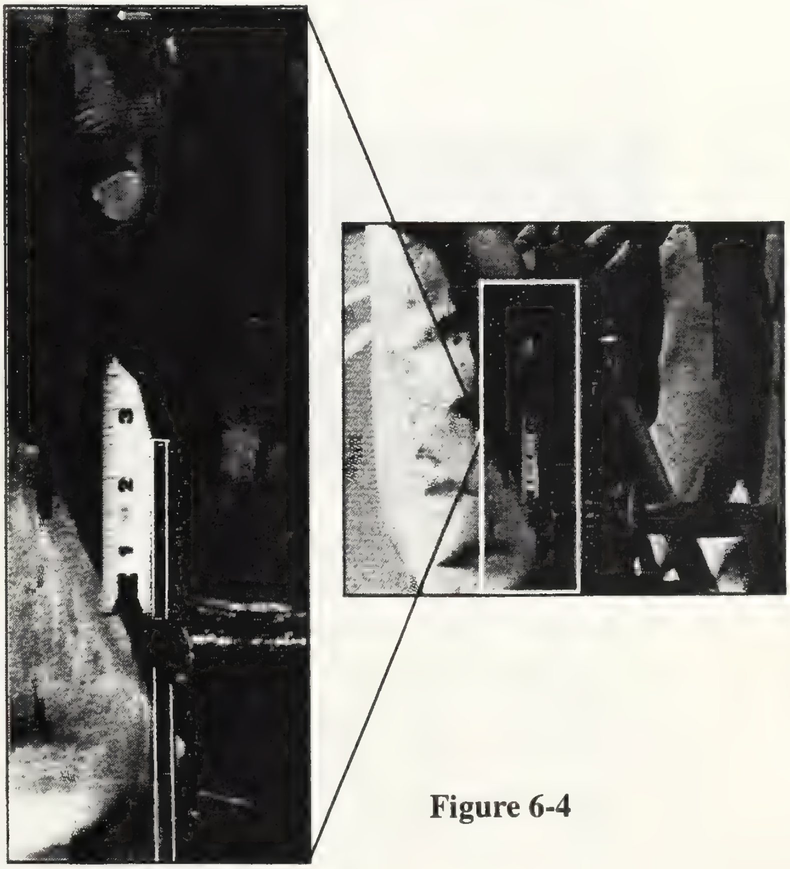


Figure 6-4

The pulverized concrete powder was collected in empty film canisters. These containers are durable, moisture tight, easy to label, and easy to transport. They contain sufficient powder to allow repeat laboratory testing if necessary.

The laboratory test required 0.1 oz. (3 g) of powdered concrete, but the project methodology called for a minimum of 0.9 oz (25 g) of powder in case repeat laboratory tests were needed. The test holes, drill bit, and sampling spoon were cleaned with compressed air after each powder sample was extracted, as shown in Figure 6-5. This is done to prevent cross contamination of the different powder samples.

Figure 6-5

All samples were labeled with the bridge name, test date, location number, and sample depth. The samples were shipped to Levelton Engineering Ltd. in Richmond, British Columbia, Canada for laboratory testing. Information on Levelton is included in Section 6.2

6.1.5 Reinforcing Steel Cover Depth Measurements

Forty to sixty rebar cover depths were measured on each deck as shown in Figure 6-6. Larger decks required more measurements. The readings were taken at representative deck locations on the closed traffic lane. Cover depth measurements were also taken at the chloride sample locations to be used in subsequent time to corrosion calculations.

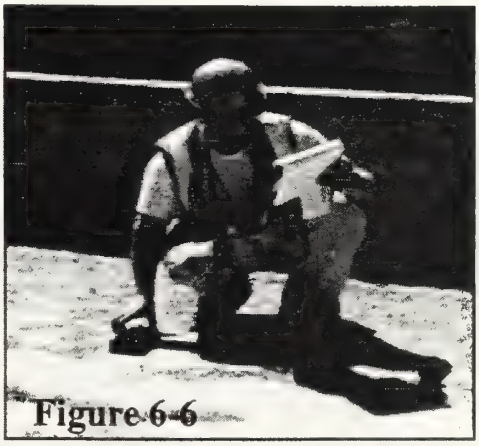


Figure 6-6

The project used was the Protovale CM cover meter. This is an extremely sensitive instrument that has been field calibrated and verified as capable of accurate readings at depths over 6 in. (150 mm). The meter was re-calibrated every six to ten readings (See Figure 6-7). The location and depth measurements were recorded and are then plotted on plan view deck diagrams. A typical plan view drawing is shown in Figure 6-9.

Figure 6-7

6.1.6 Patching the Test Holes in the Deck

The test holes were patched with Blue Line Rapid-Patch, a fluid, quick-setting, ready-mixed patching mortar. With the small sized holes, the material was mixed in small quantities in a pail and then poured into the holes (Figure 6-8). Independent laboratory tests demonstrated the good durability and low shrinkage of this material.

Figure 6-8

6.1.7 De-Mobilization of Traffic Control

After completion of testing, the work site was cleaned, traffic delineator cones removed, and traffic control signs removed. As the traffic control crew dismantled the signs, the testing crew traveled to the next bridge site, where the traffic signs were already in place.

6.2 LABORATORY TESTING OF THE CHLORIDE SAMPLES

In order to maximize the accuracy needed for this study, the AASHTO T-260 laboratory test method was selected. The test involves dissolving the powder sample in acid. It measures the total chlorides, whether free to move or chemically combined. The test procedure details are shown in Appendix D. The test method involves the extraction of chlorides with hot nitric acid, filtration, and potentiometric titration.

6.2.1 Laboratory Expertise

Levelton Engineering Ltd., of Richmond, British Columbia completed the laboratory-testing phase of the project. Levelton was recognized for their high staff qualifications and expertise. Proposals had been solicited from several qualified laboratories.

6.2.2 Quality Control

Dr. Tom Guthrie oversaw the laboratory-testing phase. Experienced analytical chemists did the laboratory work. Levelton staff performed duplication tests every ten samples, and would re-test all ten samples if the duplication test result were out by more than 10%. Reference testing was done every twenty samples. This is where a laboratory prepared aqueous solution with a known chloride concentration is tested for comparison.

SECTION 7.0

DATA ANALYSIS AND DISCUSSION

SECTION 7 DATA ANALYSIS FINDINGS AND DISCUSSION

7.1 INTRODUCTION

This section describes the chloride content data treatment, findings, and discusses the results. A detailed description of the statistical analysis is included in Appendix A.

Data analysis began with investigation for possible trends. Among others, these trends included comparing the following chloride content data sub-groups:

- wheel path versus non-wheel path,
- three depths measured from deck surface,
- magnesium chloride anti-icing versus sodium chloride deicing sites,
- chloride diffusion coefficients calculated on decks treated with magnesium chloride anti-icer versus decks treated with sodium chloride deicer
- repaired versus non-repaired decks.

The statistical analysis investigated the accuracy of observed data trends. Statistical analysis was done on both the chloride content test data and on the calculated diffusion coefficients for the individual bridges.

7.1.1 Definitions of Statistical Terms

Much of the remainder of this section describes the statistical treatment of the data. The following definitions are provided for clarification purposes:

- Coefficient of variation – a measure of the relative variation of the data points
- Confidence interval - a concept used to measure the confidence in a conclusion, as in "the conclusion is accurate 19 times out of twenty (for the 95% confidence level)";
- Confirmatory work – examination of conclusions from data for their validity and reliability; involves techniques used in hypothesis testing
- Exploratory work – data examination for trends and hypotheses

- F-test – a method used in testing data hypotheses; performed to compare the standard deviations of two data sets; the result is the acceptance or rejection of a proposed null hypothesis.

- Histogram – a graphical frequency distribution of the test data; measures the number of data points that fall between any given interval; gives a quick indication of whether the data is normally distributed

- Hypothesis testing – the procedures used to confirm the validity of conclusions from data; used in confirmatory statistical analysis

- Mean – arithmetic mean, the average value of a group of data; the sum divided by the number of data

- Normality – a measure of the realistic-ness of the data or the probability that the data is normally distributed and representative

- Normal distribution – a probability density function that approximates the distribution of many random variables; the ‘bell curve’; the normal probability shape of data

- Normal score - a measure of the observed data compared to the idealized normal data distribution

- Normal scores plot – a plot of the observed data against the idealized normal distribution

- Null hypothesis – a statistical hypothesis to be tested and either accepted or rejected in favor of an alternative. The hypothesis that an observed difference (as between the means of two data samples) is due to chance alone and not due to a systematic cause. The conclusion, reached through exploratory investigation of data, that is to be assessed by statistical methods for confirmation of its validity.

- Regression analysis – the procedures used to mathematically express the relationships between measured data; development of the functional relationship between two or more correlated variables, used to predict one variable from knowledge of the others.

- Residual – a measure of the closeness of real data to a best-fit curve from regression analysis; an expression of the error in the fit between the data and the mathematical equation at any point.

- Skew-ness – a measure of the difference from normality of a data set; lack of symmetry in the data distribution curve

- Standard Deviation – an expression of the variance in a data set; a numerical measure of the spread or frequency distribution in the data

- Transformation – a method used to re-shape the data to a form acceptable for use in statistical analysis and is confirmatory tests for hypothesis testing

- Z-test – a statistical method used in confirmatory hypothesis testing, performed to compare the averages of two data sets

7.2 DATA REFINEMENT

7.2.1 Treatment of Field Test Data

The results of the chloride tests performed on the twenty bridge decks are provided in Appendix A-1. The chloride levels are given in percent (%) of concrete mass. The field test data was converted into conventional units of pounds of chloride per cubic yard of concrete (lb/yd^3) assuming a concrete density of 3870 lb/yd^3.

7.2.2 Elimination of Data Outliers

It should be noted that one data point has been omitted from the results given in Appendix A-1. The result measured at the 2.25in. (56.3mm) depth along the right wheel line of bridge 39+09912 was omitted during a first pass of the data for errors. The chloride level of that data point was an order of magnitude higher than similar points and was removed so that it would not create error in the statistical analysis of the data.

7.2.3 Data Adjustment for Background Chlorides

In order to have an accurate comparison of the effects of different deicer chemicals on bridge decks, a correction for chlorides present in the concrete prior to deicer chemical exposure was made. The correction for these non-diffused background chlorides is described in the following section.

7.2.3.1 Methodology

Appendix A-1 shows one chloride reading at the 4.0in. (102mm) depth for each bridge. The intent of this reading was to establish a background chloride level for

the bridge. This background chloride level is due to chlorides present in the concrete at time of construction and is not due to chloride diffusion. In order to assess the effect of chloride diffusion on the bridges in this study accurately, the background levels were removed from the data before a comparison could be completed. However, upon first examination of the data taken at the 4.0in. (102mm)-test depth, it became clear that these readings were too high for chlorides typically found in concrete during construction. This meant that surface chlorides had infiltrated the 4.0in. (102mm) depth and increased the chloride content to a level above the background content. In order for the data to be properly adjusted, the background level would have to be calculated.

To calculate the background chloride levels in the bridges, the effect of chloride migration would have to be taken out of the readings taken at the 4.0in. (102mm)-depth. This first involved finding the chloride content at the 4.0in. (102mm) level due to diffusion. Fick's Second Law was applied to determine the chloride diffusion at the 4.0in. (102mm)-depth. First, the chloride levels for each bridge at the depths 0.5in. (12.5mm), 1.5in. (37.5mm) and 2.25in. (56.3mm) were averaged. Then, a diffusion time of 20 years was assumed and the average chloride level at the 0.5in. (12.5mm) depth as C_0, a diffusion coefficient was calculated for both the 0in.-1.5in. (37.5mm) depth interval and the 0in.-2.25in. (56.3mm) depth interval. These two values of D_c were then averaged to get an average D_c for each bridge. A diffusion time of 20 years was chosen because the Montana Interstate bridge de-icing program began in 1979. The use of the $C_{0.5}$ chloride level as C_0 is in accordance to conventional practice established in the C-SHRP report S-360.

Using an average D_c for each bridge, a time of 20 years and the 0.5in. (12.5mm) value as C_0, a chloride level at the 4.0in. (102mm)-test depth was calculated for each bridge. This chloride level was the theoretical amount of chloride ions that would have diffused to the 4.0in. (100mm) depth over a period of 20 years. This value was then subtracted from the measured chloride level at the 4.0in. (100mm) depth to determine what the chloride level was in the concrete prior to diffusion of surface chloride, i.e. the background chloride level.

7.2.3.2 Background Chloride Results

The results of the background chloride calculations described in the previous section are given in Appendix A-2. Overall, background chloride levels ranged from 0.00 to 0.58 lb/yd^3 (0.34 kg/m^3) with an average of 0.27 lb/yd^3 (0.16 kg/m^3) for the twenty bridges. The chloride data corrected for the average background chloride level is given in Appendix A-3.

Note: In Appendix A-2, a "*Corrected D_c*" is highlighted. When the background chlorides were computed for the 20 bridges, three instances occurred where the chloride level calculated due to diffusion was higher than the actual chloride reading. This caused the background chloride level to become negative. As this is a physical impossibility, error was the likely cause of the negative calculation. Because the chloride levels were measured values, the most likely source of error in the background chloride calculation was the accuracy of the D_c used to determine the diffused chloride level. In order to provide a more reasonable value of D_c, it was assumed that these three bridges had background chloride levels equal to the average level of 0.27 lb/yd^3 (0.16 kg/m^3). The background level of 0.27 lb/yd^3 (0.16 kg/m^3) was then subtracted from the measured chloride level at the 4.0in. (102mm) depth to give the chlorides due to diffusion. Using the 0.5in. (12.5mm) depth chloride levels as C_0, the 4.0in. (102mm) depth chloride levels (due to diffusion) and a time of twenty years, the corrected values of D_c shown in Appendix A-2 were determined for the three bridges.

7.2.4 Initial Grouping of Data

Data grouping is done for the purpose of investigating trends and possible conclusions.

A total of 400 chloride data points were measured for the 20 bridges tested. The data points were first grouped by the type of bridge deicing exposure, either magnesium chloride treated or sodium chloride treated. The data was then broken down into tests points along the shoulder of the driving surface (sample points 1, 2, 3 and 4) and points along the right wheel line (sample points 5, 6, 7 and 8).

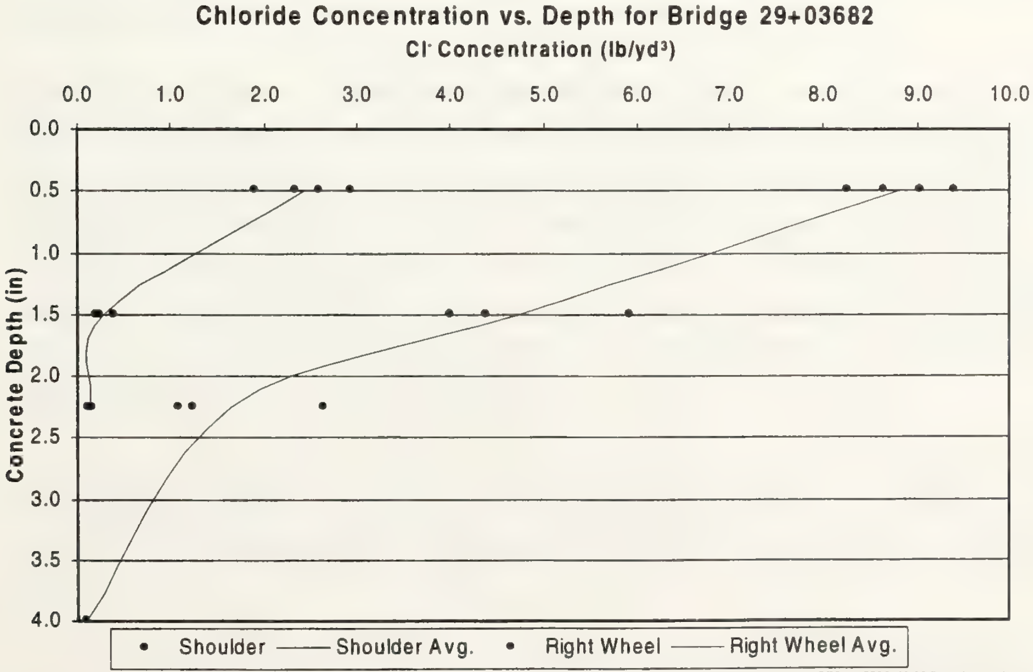


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Figure 7-1 – Typical Profile of Measured Chloride Levels

The significance of this separation is very clear when the chloride profile shown in Figure 7-1 is examined. Figure 7-1 shows a chloride profile typical of the twenty test sites.

In all twenty bridges the chloride levels along the right wheel line are at least two times greater than the levels along the shoulder. By separating the data in this manner, the significant difference in the two test lines is preserved in the statistical analysis. The chloride profiles for the twenty bridge decks are given in Appendix A-4. Finally, the data was separated by test depth 0.5 in. (12.5 mm), 1.5 in. (37.5 mm) and 2.25 in. (56.3 mm).

This arrangement of the data resulted in 18 data groups of sample sizes ranging from 6 data points to 36 data points. These data groups were then evaluated using the statistical methods described in the Section 7.4.

7.3 CALCULATION OF DIFFUSION COEFFICIENTS

Because chlorides in concrete migrate due to diffusion, the parameters describing diffusion must be determined. The diffusion coefficient of the concrete quantifies the concrete's permeability to chlorides. In order to more fully understand the effects of magnesium chloride and sodium chloride deicers on concrete bridge decks, diffusion coefficients were calculated. While average diffusion coefficients were calculated to determine background chloride levels (see Section 7.2.2), it was decided that more rigorous calculations were required for the comparison of diffusion coefficients. The following sections describe the steps taken to calculate the diffusion coefficients of the bridges tested in a more rigorous manner.

7.3.1 Methodology

Fick's Second Law of Diffusion (see Section 4) was used to determine the diffusion coefficients for the magnesium chloride and sodium chloride bridges. In order to calculate a diffusion coefficient (D_c) using Fick's Second Law, a driving chloride level (C_0) at the surface and a chloride level at a specific depth and time ($C_{d,t}$) are required. In this study it was assumed that the chloride levels measured at the 0.5in. (12.5mm) depth would provide a reasonable approximation of C_0 in the calculation of D_c. This assumption is in accordance to conventional practice established in the C-SHRP report S-360.

To produce a sufficient number of diffusion coefficients for statistical analysis, diffusion coefficients were calculated for each test hole drilled. At each hole, two values of D_c were calculated. The first value of D_c was calculated using the

corrected chloride level at the 1.5in. (37.5mm) depth and the second value of D_c was determined using the corrected chloride level at the 2.25in. (56.3mm) depth. In both cases, it was assumed that chloride diffusion had been occurring for the past 20 years (when salting of Montana Interstate bridge decks began). An average D_c at the 1.5in. (37.5mm) and 2.25in. (56.3mm) depths was then determined to give an overall D_c for each test hole. As with the chloride data, the calculated D_c values were divided by bridge deicing type (magnesium chloride vs. sodium chloride) and then by test line (shoulder vs. right wheel). This grouping gave a range of 24 to 27 average D_c values in each category. This quantity of data points was considered adequate for accurate statistical analysis.

7.3.2 Diffusion Results

Appendix A-5 tabulates the values of D_c calculated using the procedure outlined in Section 7.3.1. The D_c values are given in in^2/yr and are provided for the 0in.-1.5in. (0mm-37.5mm) depth interval, the 0in.-2.25in. (0mm-56.3mm) depth interval and an average D_c of the two depth intervals.

7.4 DATA ANALYSIS FINDINGS

The results of the statistical analysis of the measured chloride data and the calculated diffusion coefficients that were discussed in the Appendix and summarized below will later be applied to determine the effect on the service lives of bridges treated with magnesium chloride anti-icer. The times to corrosion will be calculated and compared for bridges exposed to magnesium chloride anti-icer and sodium chloride deicer. Refer to Section 10 of this report for these results.

The major findings from the data analysis are summarized below:

- Based on the overall chloride content test data, tests taken at different depths in and below the wheel paths averaged 243% higher than tests measured outside the wheel paths. This trend occurred regardless of the type of deicer chemical used, with no significant difference between the two chemicals.
- Chloride contents measured at a depth of 0.5 in. (12.5 mm) below the deck surface on bridges treated with magnesium chloride anti-icer from 1989 to 1998 averaged 18% higher than on bridges treated with sodium chloride deicers from the same time period.
- Chloride contents measured in the wheel paths at a depth of 1.5 in. (37.5mm) below the deck surface on bridges treated with magnesium chloride anti-icer

from 1989 to 1998 averaged 78% (1.42 lb/yd^3) higher than on bridges treated with sodium chloride deicers from 1989 to 1998. The range in the difference was between 31% to 125% higher for bridge decks exposed to magnesium chloride anti-icer.

- Chloride contents measured in the wheel paths at a depth of 2.25 in. (56.3mm) below the deck surface on bridges exposed to magnesium chloride anti-icer from 1989 to 1998 averaged 185% (0.61 lb/yd^3) higher than on bridges exposed to sodium chloride deicers from 1989 to 1998. The range in the difference was between 48% to 321% higher for bridge decks exposed to magnesium chloride anti-icer.
- The calculated chloride diffusion coefficients in the wheel paths on bridges exposed to magnesium chloride anti-icer from 1989 to 1998 averaged 120% (0.048 in.^{2}/year) higher than on bridges exposed to sodium chloride deicers from 1989 to 1998. The range in the difference was between 60% to 180% higher for bridge decks exposed to magnesium chloride anti-icer.

Of interest is the fact that the chloride data measured at various depths from the deck surface in areas outside the wheel paths did not show the substantial differences reported above. The data shows that magnesium chlorides diffuse more rapidly through concrete than sodium chlorides, reach the level of the steel reinforcing more quickly, and initiate corrosion more quickly, thereby reducing the service life of the exposed bridge concrete. Since deterioration is more significant when it occurs in the wheel path than outside the wheel path, the more rapid diffusion of chlorides in the wheel path significantly reduces the service life of the bridges exposed to magnesium chloride anti-icers.

The theory behind the statistical methods used in this study is provided in Appendix A for the reader's interest.

7.5 DISCUSSION OF RESULTS

The following were fundamental aspects of the design of this project:

- a sufficiently large amount of accurately sampled and measured test data was needed to provide confidence to the findings and conclusions.
- test data was taken at representative locations of sound, non-cracked concrete to assist in obtaining data that was representative of each deck typical conditions.

- the group of test bridges had to be large enough to eliminate any possible anomalies due to irregular site or application conditions. That is, the number of decks was large enough to recognise if any individual deck data was not representative of the group.

The early data analysis consisted of checking the data from the entire group as well as from individual bridges for outliers or non-representative data that should be dropped from the analysis. The data was grouped in many ways and the data distributions and standard deviations of various groupings were analyzed and compared for this purpose. Overall, the data was found to be exceptionally sound for proceeding with further analysis.

7.5.1 Wheel Path Compared to Non-Wheel Path Findings

A total of four hundred chloride tests were taken for this study. Two hundred powdered concrete samples were taken from the right wheel path and another two hundred samples from the right shoulder area outside the wheel path near the gutterline where sand and chemicals tend to accumulate from traffic. The extreme difference in the data taken from the two areas was a surprise, but from the size of the dataset, the findings appear conclusive. The higher wheel line chlorides occurred regardless of whether magnesium chloride or sodium chloride treatments were used.

7.5.2 Surface Chloride Findings for Magnesium versus Sodium Chloride Sites

Two hundred chloride tests were taken on each of the two groups of decks, magnesium chloride treated versus sodium chloride treated. Eighty tests were taken on each of the two groups at the ½ inch or surface depth.

Subsequent to the initial data analysis, additional information became available on the Interstate 90 test site locations. This information requires further discussion in relation to the data analysis conclusions.

7.5.2.1 Differences in Performance Variables at Test Bridge Sites

When the project was in the formative stage, it was thought that most of the performance influencing site conditions were similar for both the Saltese and Superior Districts, the sections of Interstate 90 where the bridges had been sampled for chloride contents. The Saltese District had been treated with magnesium chloride and the Superior District had been treated with conventional sodium chloride deicers. Similarity in the site conditions would allow an 'apples to apples' comparison of the chloride test data from the two different chemically

treated sections of road. Subsequent to the field sampling, however, discussions with MDT brought to light the fact that the two sections of Interstate 90, while similar in AADT, have differences in weather conditions. Even though they are on the same stretch of highway, the Saltese District bridges are generally located in an area of higher elevation, average snowfall and precipitation than the conventionally treated bridges from the adjacent Superior District. These differences were supported by MDT data on snow-plough miles, as well as amounts of sand and chemicals used on different districts during the winters of 1993 and 1994. The application data showed that the Saltese District roads had received much greater amounts of chemical treatment than the Superior District roads. So the question arise as to whether the variations in climate and chemical application rate would have affected the data analysis conclusions, and if so, by how much. In other words, were the two groups of bridges sufficiently similar in the important aspects that influence chloride absorption, that comparison of their chloride test data would allow valid conclusions to be drawn regarding the effects of the two chemicals?

7.5.2.2 Does Higher Chemical Application Rate Mean Higher Chlorides?

The weather data was somewhat lacking due to lack of appropriately located weather stations. Information from the road staff suggests that the magnesium chloride treated Saltese bridges receive higher amounts of precipitation and snow than the Superior District bridges.

With higher amounts of chlorides applied to decks in otherwise similar conditions, it would seem logical to have higher chloride contents absorbed in the decks. An exception to this principle has been noted by test laboratories that do accelerated time-to-corrosion testing, in which it has been found that more rapid chloride absorption results from periodically allowing the concrete to dry out between chemical applications. Apparently, chlorides are absorbed more quickly at the concrete surface when the concrete is in a drier condition than when wet. The mechanism of absorption is termed capillary absorption or sorptivity. The driving force is the suction caused by fluid surface tension. So the amount of chlorides applied does not necessarily correlate to the amount of chlorides that are absorbed into concrete if other conditions are not the same. Extra water during heavy application of magnesium chloride may tend to flush out chlorides rather than promote higher absorption. A key issue here involves the combination of site conditions that would affect the rate of chloride absorption.

So is this a situation where higher amounts of chlorides are applied to decks in similar conditions where it logical to have higher chloride contents absorbed in

the decks? Perhaps the answer is related to the acknowledged difference in precipitation on the two sections of road. Discussion with MDT indicated that the rainfall at the start of Saltese was about 60 inches per year while the average on the Superior District was about half of that.

What can we learn from the test data regarding the reported heavier chemical treatments applied to the Saltese District bridges?

7.5.2.3 Insights from the Surface Test Data

There are reasons why general engineering practice calls for the surface chloride concentrations to be measured at the ½ inch depth rather than at the actual deck surface. The reasons include the fact that the surface chloride readings tend to fluctuate significantly throughout the course of the year. Chlorides are only applied in winter, but for safety reasons they are measured in summer. After application chlorides sit on the surface, dilute as snow and ice are melted, and some are absorbed into the deck, while others are carried off the deck by runoff. The at-surface chloride content gradually builds up each winter and then decreases during the following summer. Each year the at-surface chlorides increase, gradually approaching a limit, that is related to the amounts applied and site conditions. In warm wet periods, or summer, chlorides diffuse out of the deck and are flushed away from the surface by rain. So the reason that surface chlorides are measured at the ½ inch depth is that the concentrations are more stable there throughout the course of the twelve months.

At the ½ inch depth, there is much less seasonal fluctuation in chloride content. The chloride content at the ½ inch depth tends to progressively build up over long periods of time, then acting as the driving force for the mechanism of chloride diffusion. So measurements taken at the ½ inch depth are not affected as much by the time of year tested.

The measured chloride content at ½ inch depth was an average 18% higher for the magnesium chloride treated decks in the Saltese District than that in the adjacent Superior District. Considering the much higher difference in the amounts of chemicals, sand, and miles plowed for the two districts, 18% difference in chloride content is not substantial, and was not considered to be statistically significant. That is, the difference in the surface chlorides could be due to the normally expected ranges in the two sets of test data. The significant differences in chloride content on the two groups of decks occurred at deeper depths, and the amount of difference increased with depth.

Regardless that more chemicals were applied on the Saltese District, the measured test data shows that the amounts of chlorides absorbed into the surfaces for the two sets of decks has been similar. The amount of test data should be sufficient for accuracy. 100 tests were taken at surface depth for each of the two sets of data, and the evidence from these 200 test samples supports the conclusion that similar amounts of chlorides had penetrated each group of decks. While the diffusion rates for the two groups of decks were found to be significantly different, this was not caused by higher surface chloride concentrations.

7.5.3 Deeper Chloride Findings

Magnesium chloride treated decks were found to have significantly higher chloride contents in the wheel paths at deeper than surface depth, and the difference increased with depth. They were also found to have significantly higher calculated diffusion coefficients. These findings were made from analysis of two groups of 120 tests on twenty different bridges. One group was at below-surface depth in the wheel path and the other group was from outside the wheel path.

Why did the magnesium chloride sites not have substantially higher deep chlorides in the non-wheel path locations? Why was there a difference in the diffusion rates on magnesium chloride treated bridges depending on wheel-path versus non-wheel-path? The non-wheel path test data was taken from the right shoulder area, right of the shoulder stripe, near the gutter-line where sand and de-icing chemicals tend to accumulate from traffic. These are areas where high chloride contents are often expected due the deck drainage characteristics. The apparent cause of the different diffusion rates between the two types of treated decks would appear to be related to higher moisture contents in the wheel paths when magnesium chloride is used as an anti-icing treatment. Magnesium chloride appears to attract and hold moisture in the concrete.

7.5.3.1 Insights from Non-Wheel Path Test Data

In analyzing the test data findings two possible explanations for the higher chloride contents at deeper concrete depths are:

- either the Saltese District bridge decks had been treated with chloride deicers for a longer time period than the Superior District decks
- or the Saltese District decks had received much greater amounts of chlorides due to heavier snowfall than the Superior District decks.

The problem with these explanations is that the non-wheel path test data did not show a significant between magnesium chloride treated and sodium chloride treated decks. If either of the two hypotheses shown above were true then the non-wheel path data would have showed the same trends. In other words, the non-wheel path data would have also been much higher at the deeper concrete depths.

What the test data does indicate is that there is some difference in the wheel paths that is related to the magnesium chloride treatment that causes much more rapid diffusion of chlorides at only those locations. For bridges, the wheel path locations happen to be the most critical locations in regards to the bridge deck service lives. This is because potholes and corrosion damage is most critical in the wheel paths, where traffic safety is most affected.

SECTION 8.0

EFFECTIVENESS OF DECK REPAIRS

SECTION 8 EFFECTIVENESS OF DECK REPAIRS

8.1 PURPOSE

As an aside to the main purpose of this study, this section attempts to evaluate the effectiveness of several previously installed bridge deck repairs. Since the general purpose of deck repairs is to save public funds by extending the deck service life, the chloride test data is herein analyzed for that purpose. Three interstate bridges that received deck repairs in 1993 were tested in this project for their current chloride levels.

The chloride profiles of these bridges are provided in Section 7 as Figure 7-3-1.

8.2 REPAIR TYPES

Bridges 45 + 01802 and 57 + 04722 received polymer deck overlays in 1993 while bridge 53 + 07232 had a 1.25" (32mm) latex concrete overlay placed on the deck after 0.25" (6.3mm) of the original concrete had been removed in 1993.

8.2.1 Polymer Overlays

Past studies of polymer overlays have concluded that the "effective life" of the polymer overlay repair typically ranges from twelve to fifteen years. However, if the polymer overlay is not properly installed or installed at the wrong time in the bridge's life, the effective life of the repair may be reduced. The life of the repair is defined by the duration that the repair impedes growth of active corrosion of the rebar. With polymer overlays, this is accomplished in two ways. First, the overlay prevents the replenishment of the driving chloride level at the surface. C_0 begins to decrease when the overlay is place and continues to decrease until sufficient deterioration of the overlay allows chlorides to resume migration from the surface. Second, the overlay reduces the moisture in the concrete. This decreases both the diffusion rate of chlorides into the concrete and the electrical conductivity of the deck. At the end of the life of the repair, cracking and debonding of the polymer is sufficient to allow moisture and chlorides to penetrate the concrete again. Approximately five years after the chlorides begin to penetrate the concrete again, C_0 reaches a level close to that at the surface level. In addition, with the moisture penetrating the concrete, the D_c of the concrete regains its original level. At this point, diffusion carries on as it did before the polymer overlay was added. Essentially, the polymer overlay increases the service life of the bridge by putting chloride diffusion on hold for the life of the polymer layer.

8.2.2 Latex Concrete Overlays

Latex concrete overlays behave somewhat differently than the polymer overlays described in the previous section. Latex concrete, typically, is less permeable than conventional concrete. However, the difference between the two depends on quality; lower quality latex concrete may have a similar permeability as higher quality conventional concrete. By lowering the permeability of the concrete, the diffusion of chlorides is slowed down. Secondly, the latex overlay is usually at least 1.25 in. (32mm) thick and placed on top of the existing concrete. By doing this, the C_0 that was driving diffusion in the existing concrete is virtually sealed, as was the case with polymer overlays. Without replenishment of C_0 in the old concrete, chloride levels increase much slower. Since latex concrete is not impermeable, chloride diffusion does occur in the overlay. Eventually, chlorides at the overlay to existing concrete transition reach equilibrium and chloride diffusion in the existing concrete increases. This process occurs over a longer period of time than in a normal concrete deck, thus increasing service life.

8.3 DETERMINING THE EFFECTIVENESS OF REPAIRS

8.3.1 End of Service Life

To determine the effectiveness of the deck repairs completed, the effect of the repairs on the service lives of the three bridges was examined. To do this, several steps and assumptions were made. First, the end of service life had to be defined. It is generally accepted that corrosion of rebar begins when the chloride level in the concrete at rebar depth reaches 1.2 lb/yd^3 (0.71 kg/m^3). From past experience, it has been seen that the end of service life typically occurs at a point in time when the chloride level at the rebar depth is approximately three times the threshold level, (i.e. 3.6 lb/yd^3). Therefore in defining the end of service life, a chloride level of 3.6 lb/yd^3 at the rebar level was assumed. This assumption must be interpreted with some discretion, however. While it has been observed that chloride levels of 3.6 lb/yd^3 (2.13 kg/m^3) occur at the end of service life, one must be aware that corrosion is initiated at 1.2 lb/yd^3 (0.71 kg/m^3). Therefore, if chloride levels were maintained at 1.2 lb/yd^3 (0.71 kg/m^3), sufficient corrosion would eventually end the service life of the bridge. A second assumption made, for simplicity, was that the rebar was located at a depth of 2 in. (50mm) of the original concrete. This assumption is valid for the polymer repaired bridges, given that their average rebar cover depths were measured at 2.0 and 2.2 in. (50 and 56mm) respectively. In the case of the bridge deck with latex concrete overlay, the measured rebar depth was 3.6 in. (92mm). This is because 0.25 in. (6.3mm) of the original cover was removed, but 1.25 in. (32mm) of latex concrete was added, resulting in a net increase in deck thickness of 1.0 in.

(25mm). With these two assumptions, a point on the chloride profile graph can be plotted that identifies the approximate end of service life of the bridge.

With the end of service life established, a base case for comparison of service lives had to be established. The base case was the service life of each bridge if repairs had never been done on them.

8.3.2 Projected 1999 Chloride Profiles Without Repairs

To establish a base case for each bridge, the service life of the bridge if it had not received repairs had to be determined. To do this, a chloride profile of the non-repaired bridge after 20 years of salting (in 1999) had to be generated. Several simplifying assumptions were then made in order to create this profile. First, the chloride levels along the shoulder and wheel path (blue and red lines/data points on Figure 7-3-1) were averaged to give one chloride profile for each bridge. Second, since the repaired bridges were de-iced with NaCl, the average surface chloride level (C_0) and diffusion coefficient (D_c) for the non-repaired, NaCl treated bridges (analyzed in Section 7) were calculated. Using $C_0 = 5.53$ lb/yd^3, $D_c = 0.07$ in^2/yr and a time of twenty years, Fick's Second Law was used to calculate the chloride concentration versus depth for a typical NaCl treated bridge. These theoretical profiles were then compared to the actual profiles of the repaired bridges to see if the assumptions gave plausible results.

For bridges 45 + 01802 and 53 + 07232, the theoretical curves seemed reasonable. However, for bridge 57 + 04722, the theoretical curve did not seem reasonable. The theoretical curve for this bridge gave a chloride profile that was lower in magnitude than the actual curve. Since polymer overlays will always decrease chloride levels to some extent if they are in reasonable condition, the assumed values of C_0 and D_c were incorrect. Using the actual C_0 of the repaired bridge (4.5 lb/yd^3), it was estimated that the polymer overlay had reduced surface chlorides by approximately 25% over the past 6 years. Thus if the overlay had not been placed, C_0 would have been 6.0 lb/yd^3. Given the drop in chlorides with depth for the repaired bridge, it was assumed that a D_c higher than 0.07 in^2/yr actually existed for this bridge. Several values of D_c were used and a D_c of 0.12 in^2/yr appeared to be the best fit. The theoretical and actual chloride profiles in 1999 are given in Figures 8-1-1 to 8-1-3.

8.3.3 Projected Service Lives Without Repairs

To determine the end of service life for the theoretical profiles, the time when the chloride level at the 2.0 in. (50mm) depth reached 3.6 lb/yd3 had to be calculated for the polymer repaired bridges and at the 3.6 in. (92mm) depth for the latex repaired bridge. Again, this is accomplished by using Fick's Second Law. To calculate the time, the values of C_0 and D_c at the time in question must be known. It is reasonable to assume

that D_c is relatively constant over time, therefore the values of D_c given in the previous section were used. However in this study, it has been found that C_0 tends to change over time.

Typically when a bridge is first salted, it takes several years for the chloride levels just below the concrete surface to build up to the concentration of the salting. If the levels of salting are constant, the C_0 versus time curve flattens out as time progresses. However, in the case of Montana interstate bridges, it has been observed that salting levels have increased over time (see Section 5). Thus, this curve does not flatten out, it increases over time as the salting levels increase. Using average values of C_0 calculated in this study for bridges 20 years or younger, the buildup and growth of C_0 over time was plotted. This plot is shown in Figure 8-2. Using this plot, we can estimate what C_0 may be in the future.

For bridges 45 + 01802 and 53 + 07232, it was assumed that the theoretical C_0 would increase from a level of 5.33 lb/yd^3 in 1999 to a level of approximately 8.0 lb/yd^3 at the end of service life. On Figure 8-2, this is equivalent to greater than fifty years of salt application. Using $D_c = 0.07$ in^2/yr and C_0 as above, a time of fifty years of service after salting began (1979) was calculated for bridge 45 + 01802. For bridge 53 + 07232 (latex), it was determined that service would continue longer than fifty years after salting began. Therefore, a higher C_0 was assumed, according to Figure 8-2. A C_0 of 9.5 lb/yd^3 was assumed. This gave a service life of 61 years after salting. While these numbers appear to be somewhat high (given the bridges were twelve years old when salting began) it is within reason.

Since the theoretical C_0 and D_c for bridge 57 + 04722 were higher than the other two bridges, it seems reasonable to think that service life of the bridge without repairs would be less than the fifty years calculated above. Using the same procedure, a future value of the theoretical C_0 was estimated from Figure 8-2. Since the theoretical C_0 at twenty years was higher than the value on the curve, it was assumed that the same trend would follow in the future. Thus, a C_0 at 40 years of 7.3 lb/yd^3 was assumed. Using that C_0 and a D_c of 0.12 in^2/yr, an end of service life of 35 years after salting began was determined. The lower service life when compared to the other two bridges is consistent with the higher C_0 and D_c used.

The theoretical chloride profiles at the end of service life are given in Figures 8-3-1 to 8-3-3. Notice that in all three cases, the theoretical curves intersect the 3.6 lb/yd^3 chloride level at the 2.0 in. (50mm) depth (or the 3.6 in. (92mm) depth for the latex concrete bridge), showing the assumed end of service life.

8.3.4 Actual Post-Repair Chloride Profiles (End of Service Life)

Having established the base case of service life if the deck repairs had not been made, the remaining step was to determine the service lives of the decks with the repairs that were made. For the bridges with polymer overlay repairs, the chloride profiles at the end of their repair life of fifteen years were estimated. At this point, using the D_c calculated for the base case and a C_0 appropriate for the time period (roughly 45 years of chloride exposure from Figure 8-2) a time for the chlorides at the rebar level to reach 3.6 lb/yd^3 was calculated. It should be noted that at the time of repair life end, some chlorides existed at the rebar level. The difference between 3.6 lb/yd^3 and that number was used to determine the remaining service life.

For the latex concrete repaired bridge, it was assumed that after twenty years of repair life the chlorides at the latex concrete – old concrete boundary would reach a steady state and a smooth chloride profile would result. A $D_c = 0.055$ in^2/yr was calculated for the latex overlay, with a $D_c = 0.07$ in^2/yr being used for the concrete deck. Using an appropriate C_0 from Figure 8-2 (approximately 50+ years), the remaining service life was calculated.

It was determined bridges 45 + 01802 and 57 + 04722 (polymer overlays) had service lives of 79 and 47 years after exposure to salting. Bridge 53 + 07232 (latex overlay) showed a service life of 90 years after exposure to salting.

The curves used to determine the service lives of the repaired decks are given in Figures 8-4-1 to 8-4-3.

8.4 COMPARISON OF PROJECTED SERVICE LIVES

Table 8.1 compares the results of the service life calculations performed for the three repaired bridges.

Table 8.1 Summary of Repair Effect on Service Life

Bridge	Type of Repair	Repair Year	End of Service Life Without Repair	End of Service Life With Repair	Years of Service Life Added by Repair
45 + 01802	Polymer Overlay	1993	2029	2058	29
53 + 07232	Latex Concrete Overlay	1993	2040	2069	29
57 + 04722	Polymer Overlay	1993	2014	2026	12

Several comments should be made about the results summarized above. First, the ends of service lives for both cases (with repair and without) were determined using a very limited amount of data and several generalizing assumptions. Thus the actual dates of the end of service life may vary from the dates shown above. However, since the same techniques were used to determine the end of service life for all three bridges, the comparison of service life extension amongst the bridges is reasonable. Second, a substantial difference in service life extension by the two polymer overlays was observed. This difference can be associated to the chloride conditions at time of overlay placement. Polymer overlays are most effective as a preventative measure, when chlorides in the concrete are relatively low. This was the case for Bridge 45 + 01802. Polymer overlays are less effective for bridges with higher chloride levels, since the overlay does not reduce the level of chlorides already in the concrete. Polymer overlays prevent additional chlorides from entering the concrete and slow down diffusion somewhat, but do not reduce the total amount of chlorides present. Bridge 57 + 04722 had chloride levels approximately two times those in Bridge 45 + 01802, and thus the polymer overlay was less effective than if it was applied at an earlier stage in the bridges life.

SECTION 9.0

MONTANA BRIDGE INVENTORY

SECTION 9 CHLORIDE AFFECTED MONTANA BRIDGES

The purpose of this section is to identify Montana's chloride affected bridges in two scenarios.

- first if magnesium chloride anti-icing policy is applied to the entire bridge system.
- second if the current policy of using magnesium chloride only on certain roads is continued.

Regardless of scenario, not all Montana bridges will be exposed to chloride-based chemicals during their lifetime. These bridges will have shorter service lives than those not exposed to chlorides. In order to determine the economic impact of switching to magnesium chloride anti-icing, it was necessary to first determine the long term bridge replacement costs if conventional deicing policies were continued. This baseline information will then be used in Section 10 to compare with the future bridge replacement costs if magnesium chloride anti-icers are used.

9.1 OVERALL MONTANA BRIDGE INVENTORY

The bridge inventory was analyzed to find the current individual bridge ages, estimated future replacement years and replacement costs. There are approximately 4700 bridge structures in Montana's bridge inventory. Generally, they have been constructed in the past 110 years with major booms in construction occurring in the 1930's and from 1960 to 1980. Since 1980, the number of bridges annually constructed in Montana has been declining, as shown in Figure 9-1. The number of bridges built in the past five years is at its lowest level since the 1920's.

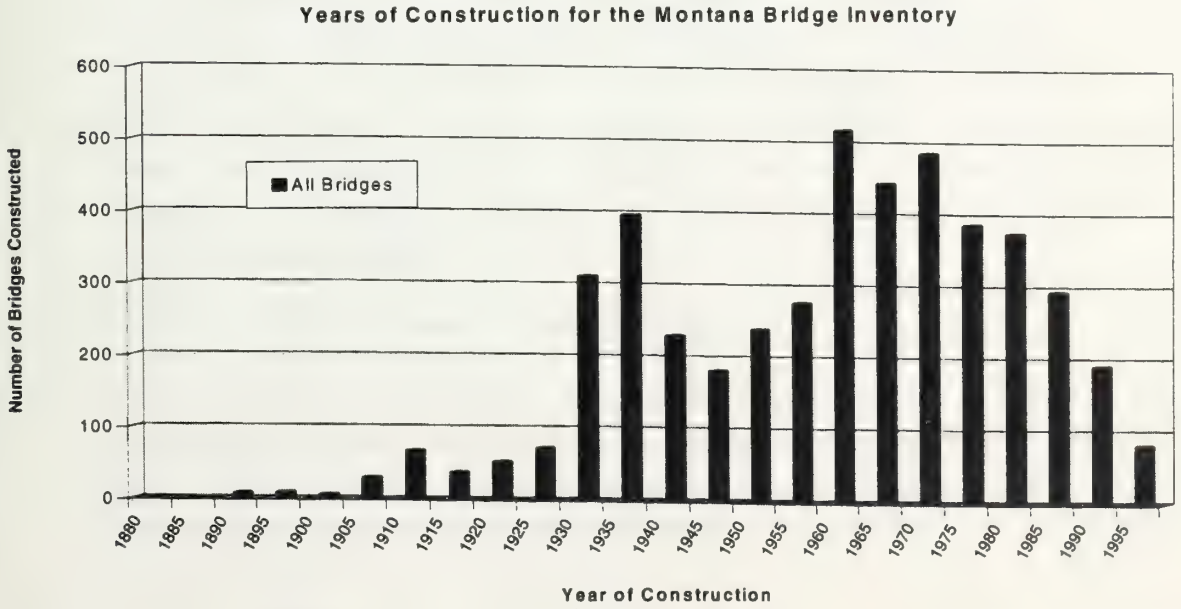


Figure 9-1

9.1.1 Future Bridge Replacement

Although the rate of new bridge construction is currently low, the existing inventory has significant replacement value. When these structures have to be replaced, greatly increased budgets will be needed. Figure 9-1 illustrates the boom periods and the bust periods of past bridge construction. In the same way that the baby boomer generation affected many trends in the 1960's and 1970's, boom periods of bridge construction will either have a future ripple effect on bridge replacement or substantial reductions in the levels of bridge service will result.

As the existing bridges reach the end of their service lives, budgets will be needed to fund construction of replacement structures. In order to allow comparison with the costs of maintaining the bridge infrastructure if magnesium chloride is used for anti-icing, the annual bridge replacement costs were first calculated for the scenario of current pavement management using conventional roadway deicers. The service lives estimated and discussed below are based on experience in other jurisdictions and discussions with appropriate MDT bridge management staff.

9.2 MONTANA BRIDGE CATEGORIES BY AMOUNT OF CHEMICAL TREATMENT

Every bridge in the Montana inventory has its own service life and its own unique characteristics, but for the purpose of this study, the structures have been divided into three major service life categories based on their exposure conditions. The more chlorides a bridge is exposed to, the shorter its service life will be. Only about two thirds of Montana bridges are expected to be exposed to chloride-based chemical treatments in their lifetimes. The below bridge exposure categories and estimated bridge service lives may not exact, but they are suitably accurate for the purposes of this study. The service lives of the bridges are based on numerous studies that have been completed over the years as well as expert opinion. These predicted service lives do not take into account the general trend of using increasingly large amounts of deicer, which may result in shorter lives or increased rehabilitation costs.

9.2.1 Heavily Treated Montana Bridges

Heavily treated Montana bridges are generally Interstate bridges exposed to high-speed truck traffic and heavy chemical treatment with deicers or anti-icer application. Based on experience in North America they are estimated to have average service lives of 50 years. They are identified as having been built as part of the interstate system, and they tend to

be wider and have heavier traffic than the average bridge. Analysis of these bridges in Montana shows the average annual daily traffic (AADT) for this group to be approximately 6000. Because of the heavy traffic, they also receive more chloride-based chemicals, which creates more aggressive corrosion conditions for the bridge deck and overall structure and consequently reduces their expected service life. The average service life of the heavily treated bridges will be about fifty years, but the range in service life will likely be from 35 to 65 years. These bridges will get the most de-icing chlorides and have the shortest service lives of Montana bridges.

Heavily treated bridges have the shortest predicted service lives of the three categories. The predicted average service life is fifty years if the bridges are only subjected to sodium chloride deicer. Several reasons for the reduced service lives of Heavily treated bridges compared to Moderately treated and 3 bridges are as follows:

1. The Heavily treated bridges have the largest volumes of traffic. The average Interstate bridge in Montana has an ADT of 6000. The Interstate highways have the highest posted speed limits and on average, the most truck traffic. Truck loads on bridges cause higher stresses, more and wider cracking, which allows quicker ingress of chloride ions to initiate corrosion.

2. Since the Interstate bridges have the highest traffic speeds and volumes, they also have higher quantities and more frequent applications of deicer needed to keep the deck ice-free. Chloride based deicers are very corrosive to embedded steel.

3. Interstate bridges sometimes become functionally obsolete. This means that the bridge must be replaced before its condition dictates that it should be replaced. In this situation the structure is usually replaced because it can no longer accommodate increasing traffic volumes. Extra lanes may be required on the bridge deck, or the roadways that go underneath the structure need to be wider but they cannot be made wider since the bridge abutments are in the way.

9.2.2 Moderately Treated Montana Bridges

Moderately treated Montana bridges are defined for the purposes of this study as generally the more heavily traveled non-interstate bridges, that is, with current annual ADTs greater than 500. This is the broadest of the three Montana bridge exposure categories, since it includes moderately traveled rural bridges as well as heavily traveled urban bridges. Overall, the AADT values of Montana bridges in this category range from 500 to 35,000, but the average value was found by analysis to be approximately 3000. There is generally less truck traffic on moderately treated bridges than on heavily treated bridges. Generally the bridges in this category are in a moderately corrosive condition.

They receive deicers in winter, but typically less than heavily treated interstate bridges. The average service life of these bridges will be about 65 years with an expected range of from 45 to 85 years.

. There is wide variation in the types of moderately treated bridges and the amount of traffic they have. The 65-year service life prediction is intended as an average service life prediction. That is, that some bridges will last longer, and others will not last that long, but in the overall picture, it is felt that these differences will balance out. The accuracy of this study is largely independent of the estimated service lives.

9.2.3 Non-Chemically Treated Montana Bridges

These are generally lightly used bridges with AADTs less than 500 and use by very few heavy trucks and therefore were estimated to have longer than normal service lives due to their light use and lack of exposure to chloride based chemicals. The average AADT of a Montana bridge in this category is about 150 vehicles per day. The average service lives of these bridges should be about eighty years with a range of sixty to one hundred years. These bridges will not be included in magnesium chloride economic impact calculations that follow in Section 10.

9.3 BRIDGE INVENTORY ANALYSIS

For the purpose of this study, the Montana bridge inventory was divided into three categories by their approximate service life ranges. The total deck area for each bridge category was calculated, and from that area the approximate total bridge replacement value of each category was computed. Detailed breakdowns of the different number and size of the bridges in each category are included in Appendix B.

9.3.1 Number of Bridges

The approximate breakdown of these Montana bridge inventory into the three major categories are as follows:

CATEGORY	NUMBER
• Heavily Treated Bridges	840
• Moderately Treated Bridges	1110
• Non-Treated Bridges	2750
• Total Montana Bridges	4700

9.3.2 Total Deck Area

The deck area for each of the major bridge categories has been calculated and the results are presented below:

CATEGORY	DECK AREA
• Heavily Treated Bridges:	6,645,000 ft^2 (617,000 m^2)
• Moderately Treated Bridges:	5,340,000 ft^2 (496,000 m^2)
• Non-Treated Bridges:	5,360,000 ft^2 (498,000 m^2)
• Total Bridge Deck Area:	17,345,000 ft^2 (1,611,000 m^2)

9.3.3 Bridge Replacement Value

The estimated total cost to replace the existing bridge inventory is presented below for each of the bridge categories. The values shown represent the Montana public's economic investment in the bridge portion of the transportation system. The costs are shown in today's dollars and do not account for the future effects of inflation. A cost of \$108/ft^2 (\$1150/m^2) of deck area was assumed for all of the structures in the inventory. This estimated unit cost includes replacement, engineering, demolition, and detour costs.

CATEGORY	REPLACEMENT VALUE
• Heavily Treated Bridges	$710,000,000
• Moderately Treated Bridges	570,000,000
• Non-Treated Bridges	573,000,000
• Total Replacement Value	$1,853,000,000

Note that the replacement costs are based on replacing the bridge with a new bridge that is the same size as the original structure. This is a conservative estimate since bridges are typically replaced with larger/wider structures due to increased standards and higher traffic volumes that have occurred during the typical 50 to 80 year life of an average bridge.

9.3.4 Summary of Montana Bridge Inventory

Bridge Category	Number of Bridges	Deck Area of Bridges	Cost of Bridge Replacements
Heavy	840	6,645,000 ft^2 (617,000 m^2)	$ 710,000,000
Moderate	1110	5,340,000 ft^2 (496,000 m^2)	$ 570,000,000
Non-De-Iced	2750	5,360,000 ft^2 (498,000 m^2)	$ 573,000,000
Total	**4700**	**17,345,000 ft^2 (1,611,000 m^2)**	**$ 1,853,000,000**

The summary chart above shows that of the three bridge exposure categories defined for this study, the most highly invested category is the Heavily Treated Bridges, the Interstate system. The total number of bridges in this group is less than the other two categories. Since these bridges are exposed to the most aggressive corrosion conditions, the importance of maintaining these bridges to avoid high future expenditures is apparent.

9.4 BRIDGES CURRENTLY TREATED WITH MAGNESIUM CHLORIDE

There are approximately 250 bridge sites that are currently being treated with magnesium chloride, and the replacement value of these sites totals $350M. The site list of the magnesium chloride treated bridges has been provided by MDT and is included in Appendix E. Also a map of Montana with all of the areas that are currently receiving the anti-icer highlighted is included in this report. The map is located in an envelope in Appendix E. The bridge sites are generally located immediately around the major centers in the State (including Great Falls, Helena, Missoula, Butte, Kalispell, Shelby, Havre, Sidney, Miles City, Billings, Bozeman, Glendive, Lewiston, and others) and along the western sections of I 90.

SECTION 10.0

ECONOMIC IMPACT OF MAGNESIUM CHLORIDE

SECTION 10 ECONOMIC IMPACT OF MAGNESIUM CHLORIDE

The purpose of this section is to use the field test data and conclusions to determine the economic impact of magnesium chloride on Montana bridges. First, the effect on service life will be investigated. The baseline cost information developed in Section 9 is used for comparison with the bridge replacement costs using magnesium chloride anti-icers.

10.1 BRIDGE SERVICE LIFE

Every bridge structure is unique and has its own characteristics and anomalies. These characteristics relate to the service life of any structure. Different environmental conditions, as well as different traffic volumes driving on the structure at different speeds, and different types and amounts of deicing solutions can all contribute to the service life of a structure.

10.1.1 Historical Trends in Service Life

As time progresses, bridge decks are being placed into increasingly corrosive environments. As traffic volumes increase, so does the amount of deicer that is placed on the deck every winter. More efficient anti-icers are also being applied, such as magnesium chloride. New bridge decks can better accommodate this increase by using high performance materials, corrosion inhibitors, or even non-corrodable reinforcement. However, structures that are more than twenty years old are more susceptible to the increase in corrosion activity.

10.2 FUTURE BRIDGE REPLACEMENT NEEDS

10.2.1 Montana Bridge Construction Years and Ages

Montana's 4698-bridge inventory was constructed during the previous 110 years, therefore the bridges vary in age. Category 1 bridges were constructed in the boom times from 1960 to 1980. The varying bridge ages and the varying service lives for different bridge categories complicate the economic impact calculations. Figure 10-1 is a simple graph based on bridge inventory construction years. The figure shows the numbers of bridges constructed per five-year period since 1880 for the Montana inventory. The bridges are sub-divided by service life category. Note that during the boom construction period of 1960 to 1970, close to 100 bridges of all types were built annually.

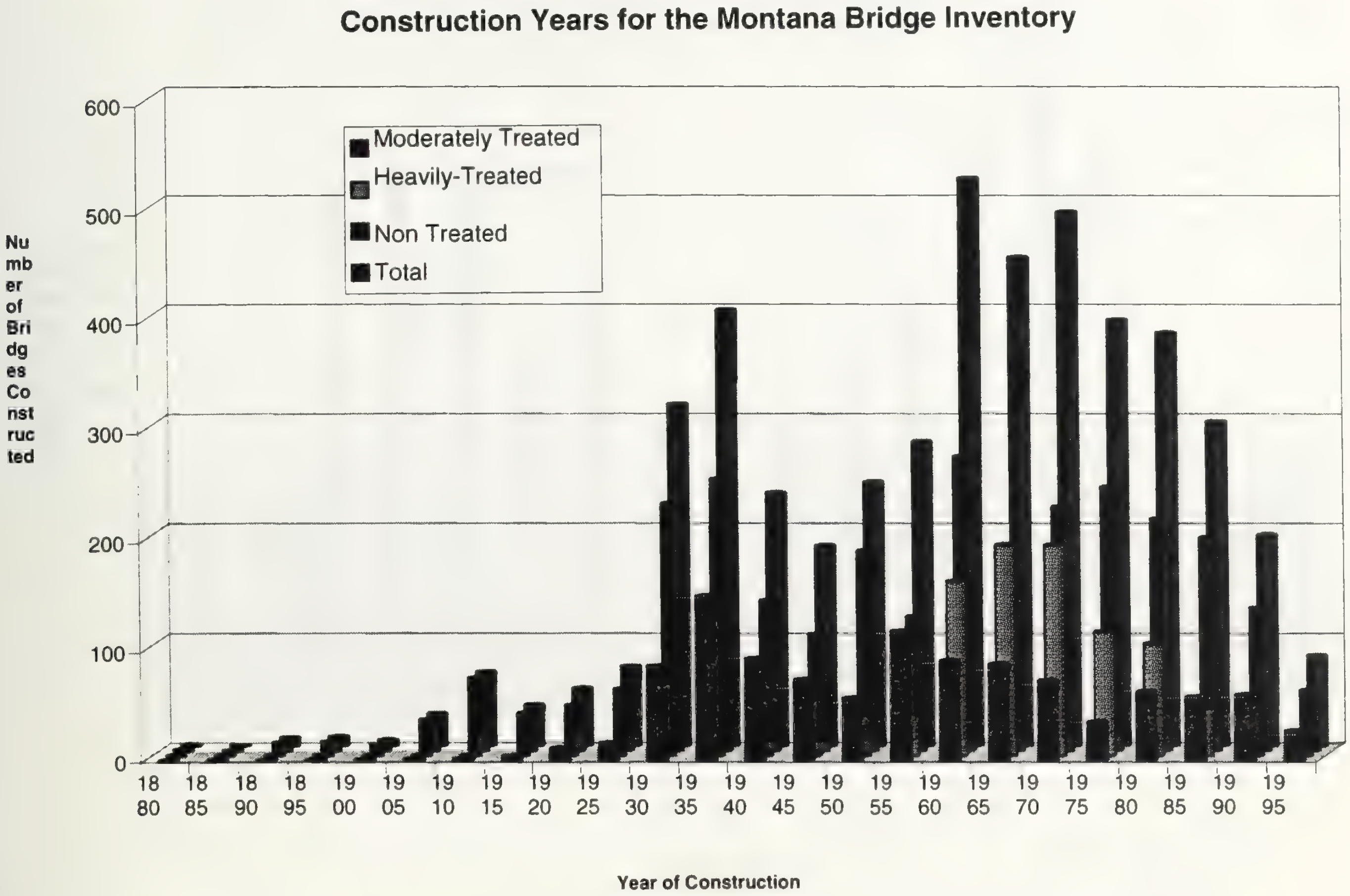


Figure 10-1

10.2.2 Predicted Bridge Replacements with Conventional Deicing Practice

Future bridge replacements are found by adding the average service lives of each bridge to its construction year and then summing the numbers of bridge replacements for each five year period, as shown in Figure 10-2. Since this figure looks at an eighty-five year period, some bridges will be replaced more than once in the analysis period. The annual numbers of bridge replacements can be obtained by dividing the graph values by five. This scenario of future replacements is based on the sole use of sodium chloride deicer.

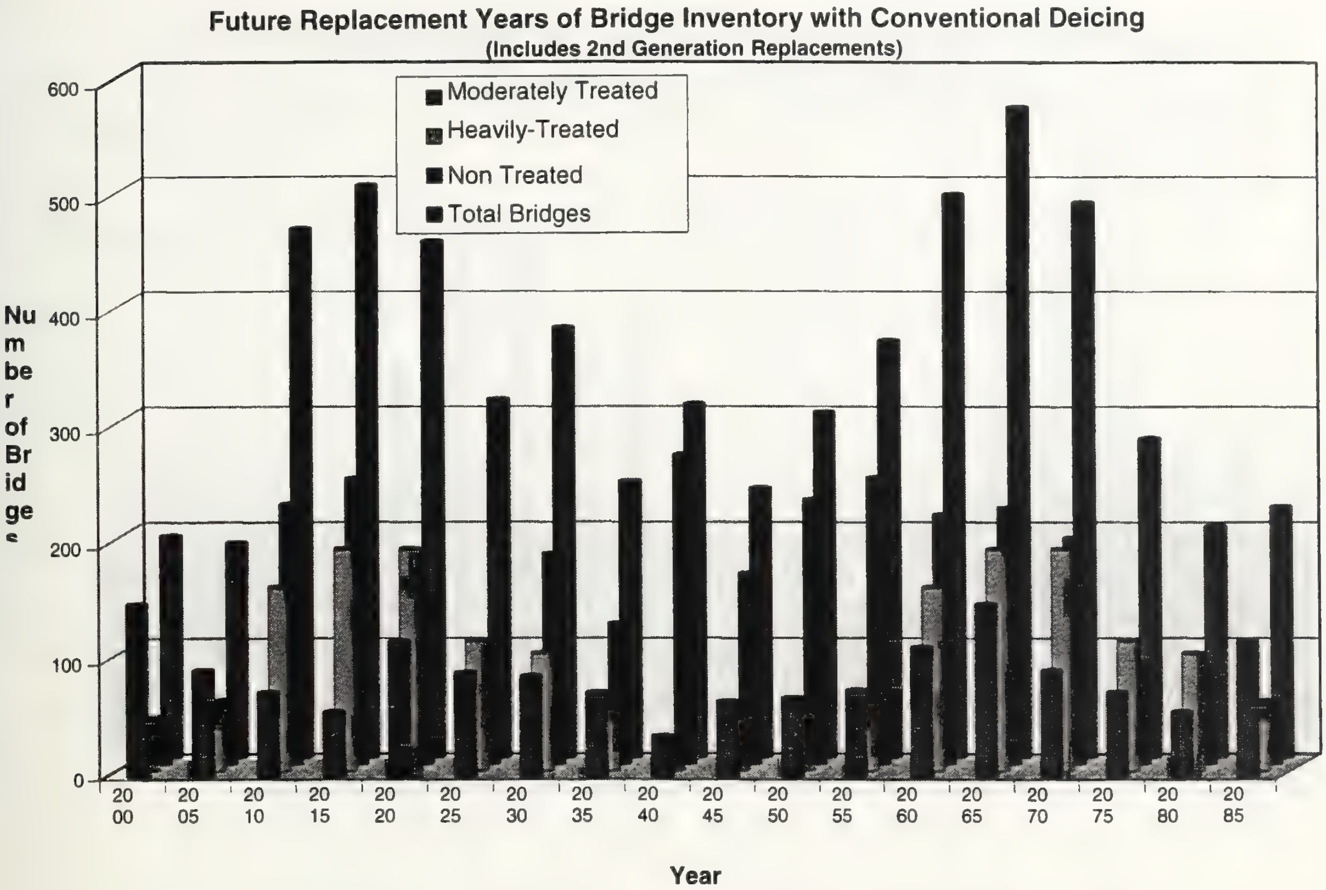


Figure 10-2

Due to the current ages of the Category 1, heavily treated bridges, the future bridge replacement costs are projected to soon greatly increase. Figure 10-2 shows rising budget needs for the next twenty to thirty years. Note that the figures are for five-year periods. The annual budget needs can be obtained by dividing the graphed figures by five. The budgets needed for annual bridge replacements to maintain the current levels of service will more than double compared to current needs. The bridge replacement needs for the next five years are predicted to be double those of the five-year period 1995 to 2000.

The most expensive bridges to replace are the Interstate bridges, and the majority of these will need replacement between 2010 and 2025. Figure 10-3 shows the projected future budgets per five year period needed to replace the bridges at the times outlined in Figure 10-2. Again, annual budget needs are found by dividing the graphed numbers by five. The above figures are based on continuing current deicing practice using sodium chloride rather than magnesium chloride anti-icer.

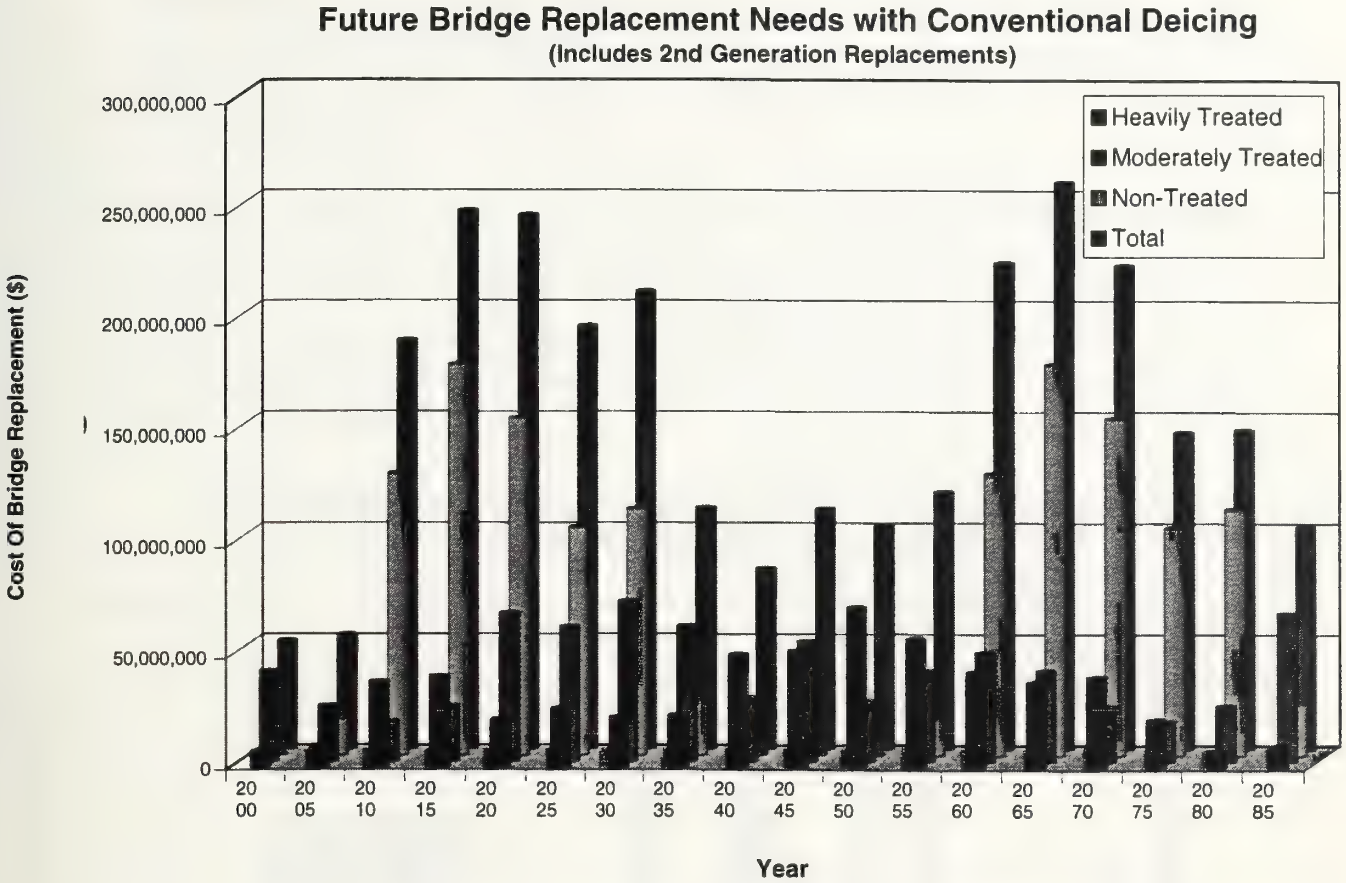


Figure 10-3

Figure 10-3 above shows that bridge replacement budget needs with current deicing practice will peak between years 2015 to 2025. Each of the two five-year periods will require 3.5 times more budget than the period 2000 to 2005. The major future replacement needs occur in Category 1, the Interstate bridge system. A likely possibility is that due to lack of adequate funding the service levels or typical bridge conditions will decline. Another likely possibility is that as funding becomes focused on reacting to replacement of deteriorating bridges, proactive measures such as timely rehabilitation may be sacrificed to meet the more immediate needs. Additional graphs showing future Montana annual bridge replacement needs and expected annual bridge replacement numbers from the years 2000 to 2035 are included as Figure 10-4 and in Appendix C.

Figure 10-4 plots the future bridge replacement needs for Category 1 and 2 conventionally treated bridges, neglecting the effects of inflation over the next 35 years. The horizontal line in Figure 10-4 is the average annual expenditure, $24 million, for the entire 35-year period. This value may represent a more realistic scenario since budgets tend to stay consistent rather than fluctuate from year to year. In any group of bridges

some will have to be replaced earlier than predicted and others will last longer. Actual bridge replacements can be scheduled to level out the peaks and valleys in the future required budgets by allowing changes to the average bridge condition and level of service provided to the public.

The annual average expenditure provides a realistic guideline for estimating future budget needs. A general guideline for the average annual budget needed to maintain the inventory is approximately 2% of the infrastructure replacement value. The replacement value of the Category 1 and 2 chemically treated bridges is $1.3 billion. 2% of the total treated bridges is $26 million, which is reasonably in agreement with the detailed analysis results of $24 million.

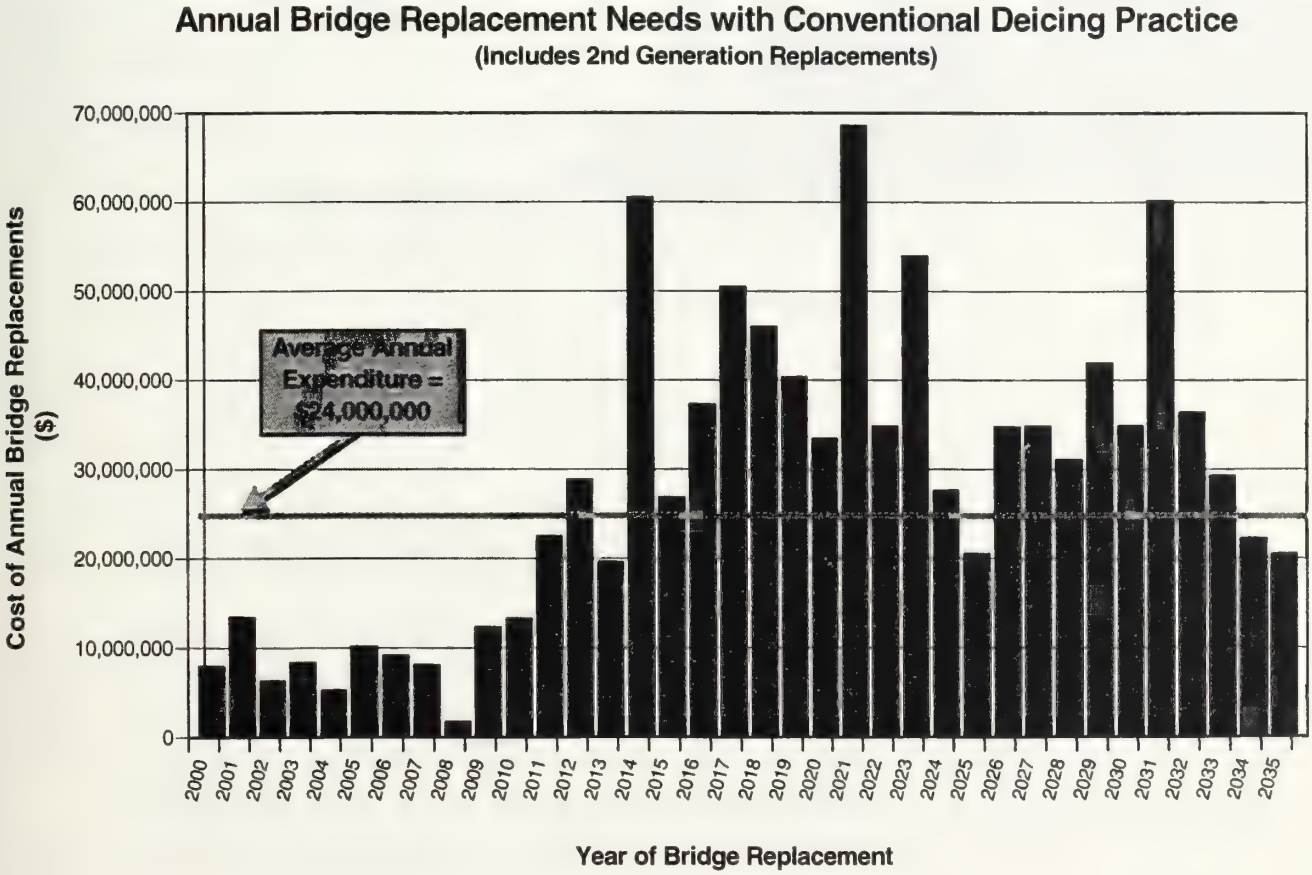


Figure 10-4

What if future bridges cost more due to monetary inflation and higher construction and environmental standards? Figure 10-4a is similar to Figure 10-4, except that a 6% annual increase in replacement costs is included to represent inflation and increased standards, which may be related to environmental protection and public/worker safety. The average annual bridge replacement needs increase to $110 million for the 35-year period.

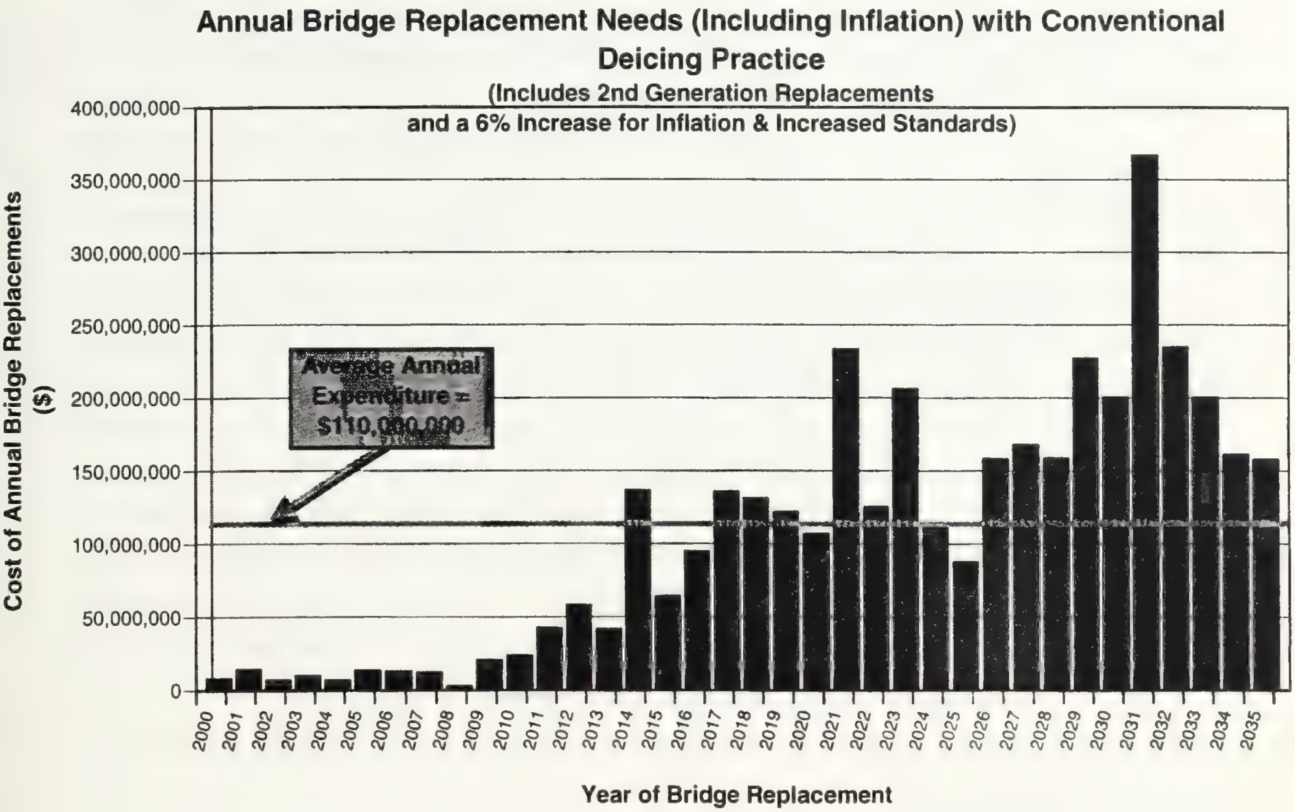


Figure 10-4a

10.4 THE EFFECTS OF MAGNESIUM CHLORIDE

Data analysis in Section 7 quantified the effect on bridge service lives resulting from the use of magnesium chloride. For existing bridges the service lives will begin to be reduced when magnesium chloride anti-icing begins. This reduction in service life will affect the future bridge replacement needs. Shorter service lives of treated bridges equals higher replacement budget needs. Replacement needs for non-treated bridges are not included in this cost analysis, since we are addressing the possible changes resulting from type of anti-icing treatment.

10.4.1 Effect of Magnesium Chloride on Bridge Service Life

As Reported in Section 7.0 a difference was found between the diffusion rates of magnesium chloride and sodium chloride in the wheel paths of concrete bridge decks. Bridges treated with magnesium chloride had an average diffusion coefficient, D_c, of 0.088 in^2/yr (0.57 cm^2/yr) while bridges treated with sodium chloride had an average D_c

of 0.040 in^2/yr (0.26 cm^2/yr). The difference in diffusion coefficients creates a difference in the time that it takes for rebar corrosion to begin, the time to corrosion, for bridges exposed to the two chemicals. The difference in times to corrosion equals a reduction in service life for bridges exposed to magnesium chloride.

To determine the effect of magnesium chloride on service life, Fick's Second Law (See Section 4.0) was used to calculate the time to corrosion for magnesium chloride treated and sodium chloride treated bridge decks. The calculations were done using the test data conclusions from this study. First, a surface chloride level (C_0) of 6.8 lb/yd^3 (4.0 kg/m^3) was assumed for all bridges. This was the average value for all surface level chloride readings taken in this study. Second, it was assumed that the time to corrosion would be achieved when 10% of the deck rebar was actively corroding. It was also assumed that the variation of rebar depth would be ± 0.3in. (7.1 mm). A time to corrosion for the magnesium chloride treated and sodium chloride treated bridges was calculated for rebar depths ranging from 1.75 in. to 4.0 in. (44mm to 100mm). The results of these calculations are shown in Figure 10-5. Figure 10-5 illustrates the relationship between rebar cover depth and reduced service life due to reduced time to corrosion. As the cover depth increases the reduction in service life also increases. The difference in time to

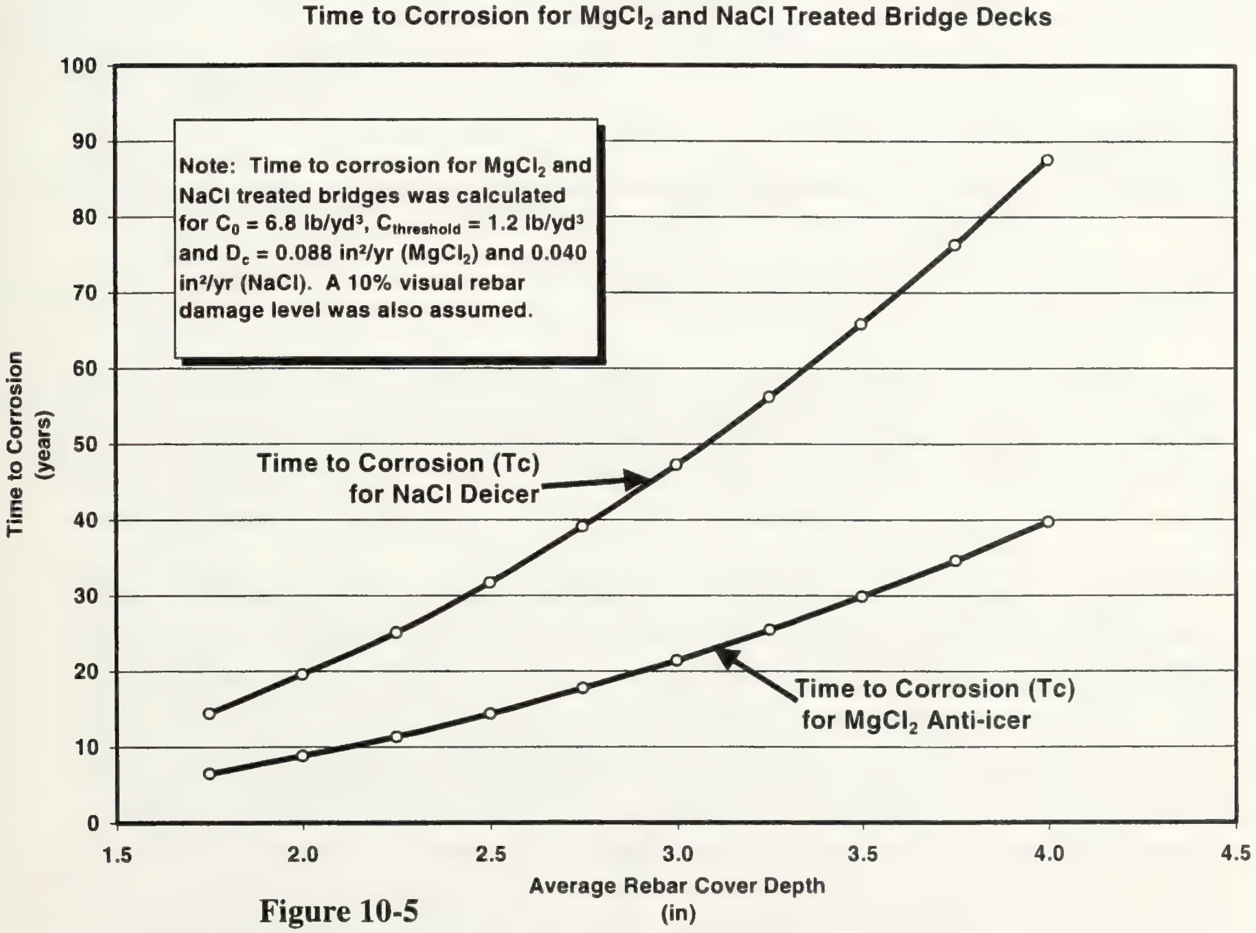


Figure 10-5

corrosion for bridges of different rebar cover depths exposed to the two chemical types is plotted in Figure 10-6.

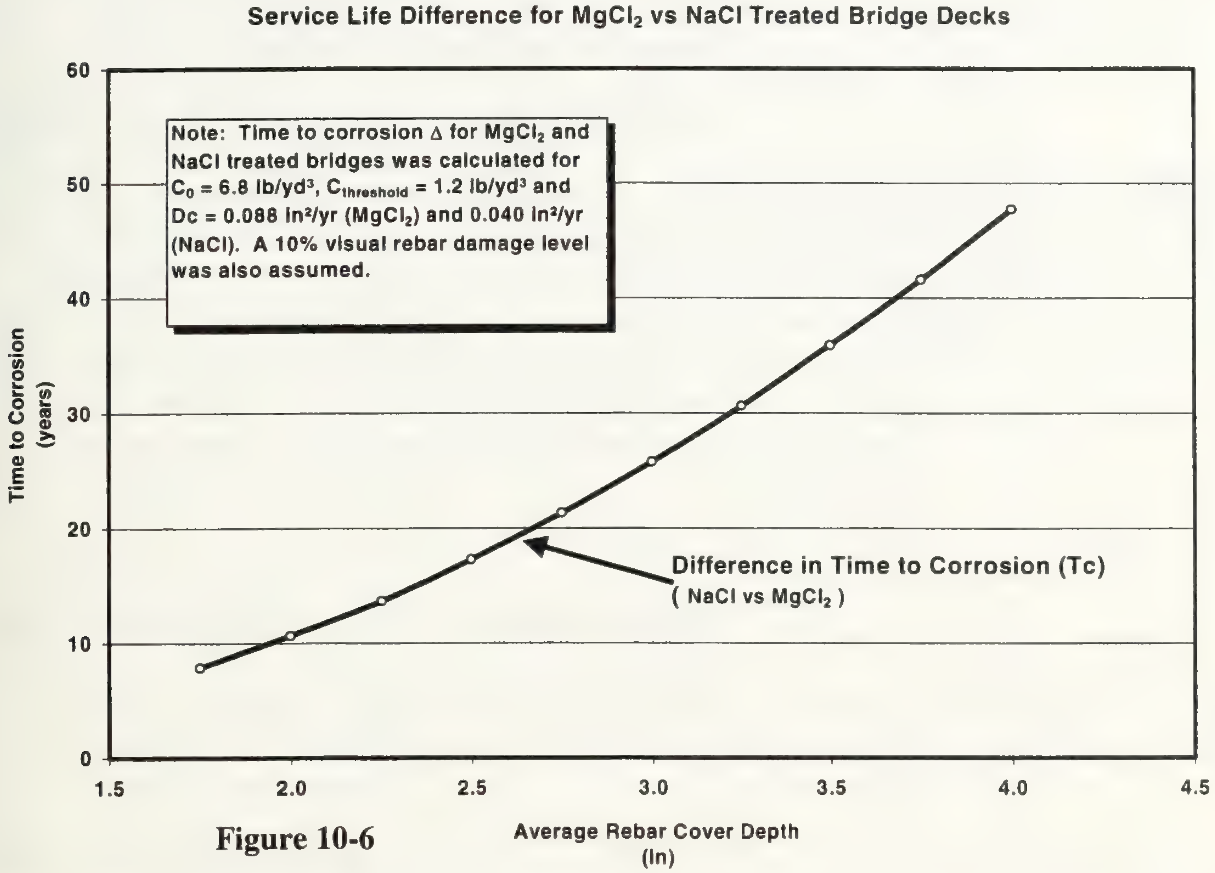


Figure 10-6

Using the results of Figure 10-6, it can be seen that for a rebar depth of 2 in. (50mm), the reduction in service life of magnesium chloride treated bridges compared to sodium chloride treated bridges is 11 years. When the cover depth is 3 in. (76mm), the reduction in service life is 27 years.

Montana bridges currently vary in age up to 110 years. The expected range in cover depths varies as bridge design standards have changed during those years. Two to three inch cover depths are reasonable for a large portion of the infrastructure. Considering the range of bridge service lives to be from 50 to 80 years, service life reductions of 11 to 27 years equate to percentage reductions in life of between 14% to 54% for bridges subjected to magnesium chloride deicing. Overall an average reduction in remaining service life of 20 to 30% from use of magnesium chloride anti-icer will be used in the following calculations. This is thought to be a conservative value, since none of the test bridges involved the use of only magnesium chloride. It is reasonable to think that the sole use of magnesium chloride would result in even greater reduction in life.

It appears logical that when the rate of chloride diffusion for magnesium chlorides is double the rate for sodium chlorides, that service life would be half. Also, when future expenditures are required sooner in time, these costs increase due to the value of money being more now than it will be later. Both of these concepts suggest that the economic impact may be greater than the 20 to 30% range.

10.4.2 Effect of Magnesium Chloride on Old Bridges

As determined in the previous section, the application of magnesium chloride conservatively decreases the *remaining* service life of a bridge by 20 to 30%. For example, if a heavily treated bridge has a service life of 50 years but the bridge is already 40 years old before magnesium chloride comes into use, the magnesium chloride would have less effect on service life, reducing only the remaining service life by 20 to 30%. In this case, the remaining service life would be reduced from ten years, with sodium chloride only, to seven or eight years with magnesium chloride.

10.5 FUTURE BRIDGE REPLACEMENT COSTS

Since magnesium chloride reduces service life and causes replacements to be done sooner, involving more expensive dollars, the effect on future costs with de-valued dollars will be explored.

10.5.1 General Methodology

Life cycle cost analysis involves a comparison of future costs for various methods of managing the bridge inventory. Present worth analysis is useful to determine which management option is the most cost-effective solution in the long run and by how much.

Future bridge replacement expenditures are converted into today's (year 2000) dollars and summed for each option. A 4% future cost of money is assumed, representing the difference between the return the money would likely earn and the annual inflation rate.

10.5.2 Interpretation of Cost Analysis Results

The net present worth cost analysis procedure summarizes the life cycle costs of each of the management options over the entire analysis period, beginning with the year 2000. When all of the expenditures are converted to year 2000 dollars and are summed for the entire analysis period, the lowest total will be the most economical option. If the resulting amounts are relatively close (<5% difference) then these options should be considered equal since it is impossible to predict into the future with 100% accuracy. In

this case, other factors should be taken into account to determine which option better suits the project's needs.

The effect of magnesium chloride on bridge replacement cost is complicated as shown by Figures 10-7 through 10-12, which illustrate the 5 year average budgets needed over a very long period of time for the two deicing scenarios.

Figures 10-7 and 10-8 compare the number and cost of bridge replacements for the bridge inventory if it is deiced with sodium chloride only or if a combination of sodium chloride and magnesium chloride is used. These figures show a 20% decrease in the remaining service life of the bridge inventory for the moderately and heavily treated bridges. Figures 10-9 to 10-12 are similar to Figures 10-7 and 10-8 except with 25% and 30% decreases in the remaining bridge service lives.

As the effects of magnesium chloride increase, the bridge service lives decrease and the replacement costs move closer to the present day. This trend is consistent regardless of the amount that magnesium chloride decreases the remaining service life of the bridges.

A second manner of presenting life cycle costs is to represent them as the annuity payments that would need to be invested annually over the analysis period to be equivalent to the present worth sum. The difference in the annuity values between the two options represents the annual savings resulting from using the lowest option. The option with the lowest annuity is the optimum economic choice for the analysis period.

10.5.3 Economic Analysis of Magnesium Chloride Anti-icer – First Management Scenario

This study compares two bridge management options. The first illustrates the effects of using magnesium chloride anti-icer on all bridges presently treated with chemicals. The other represents the effects of continued use of magnesium chloride anti-icer on bridges currently being treated with magnesium chloride anti-icer. The bridges that have been included in the economic analysis are the Category 1 and Category 2 chemically treated bridges only. The non-treated local road bridges have been excluded from this analysis. Therefore there are approximately 1,950 bridges in this comparison with a total current replacement value of $1.3 billion. The replacement dates resulting from sodium chloride treatment are based on fixed bridge service lives that are based on the amount of chemical treatment. It was assumed that Category 1, heavily treated, bridges have average service lives of 50 years and moderately treated bridges have longer average lives of 65 years. These values have been added to the bridge construction years to determine the replacement date. There is a varied effect of magnesium chloride on bridge service life, because there are a number of other factors (ie. rebar cover, bridge age, etc.). A 20%,

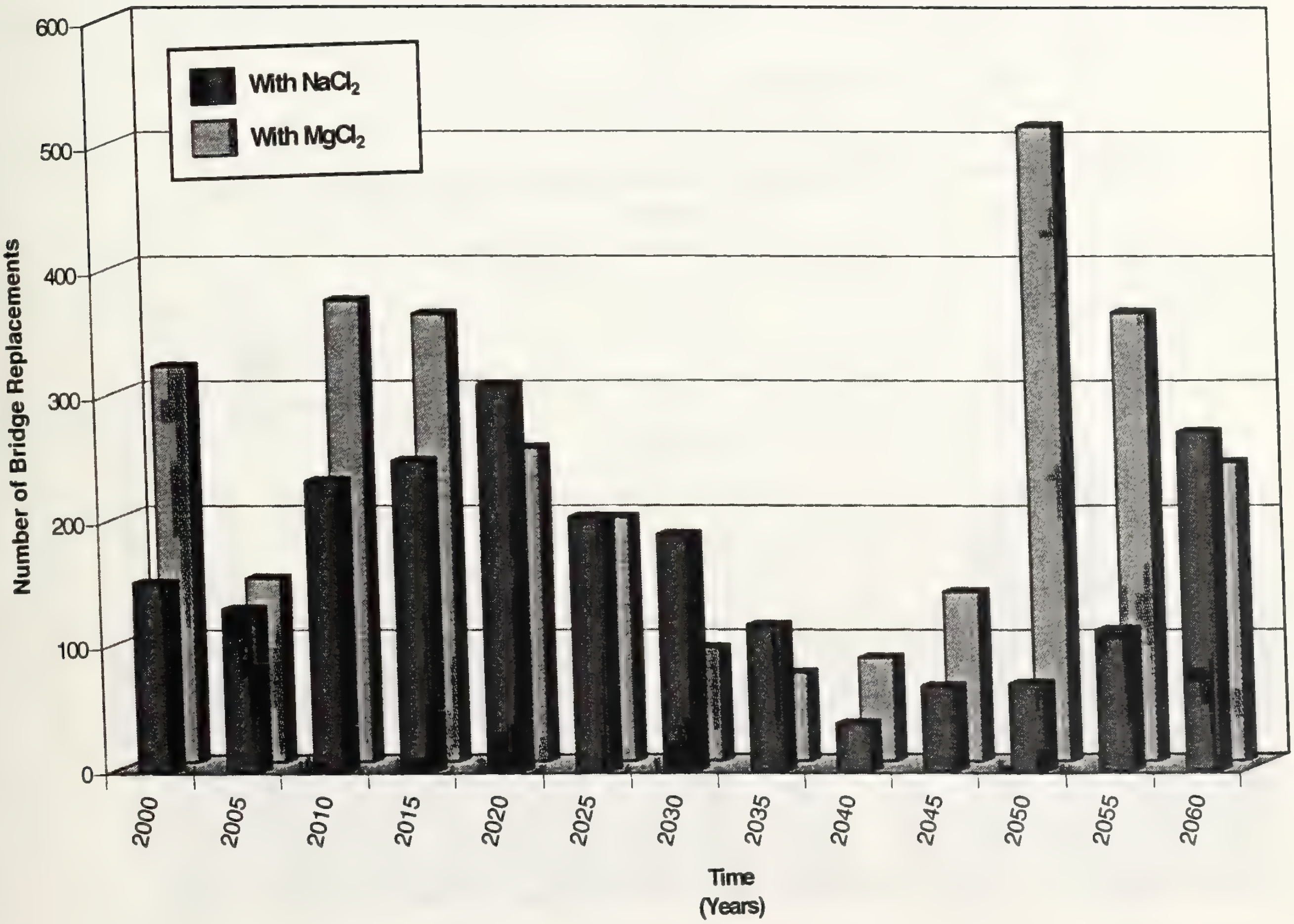
25%, and 30% reduction in service life due to magnesium chloride was used for the analysis. These assumptions are described in more detail in Section 9.1 and 10.1.

10.5.3.1 Application of the Life Cycle Cost Analysis to the Montana Inventory

The expenditure amounts and bridge replacement years that were used in the life cycle cost analysis are shown in Figures 10-7 to 10-8 below.

Two separate analysis periods were used in this analysis, but any period could be used and the general trend of the results would be the same. A 60-year analysis period was selected to encompass all of the Category 1 and Category 2 bridge replacements. The second analysis period was selected as twenty years, representing the more imminent needs of the near future.

Future Bridge Replacement Needs for Two Scenarios on all Presently Treated Bridges If $MgCl_2$ Reduces Service Life by 20%



Future Bridge Replacements Needs for Two Scenarios on all Presently Treated Bridges

Figure 10-9

If $MgCl_2$ Reduces Service Life by 20%

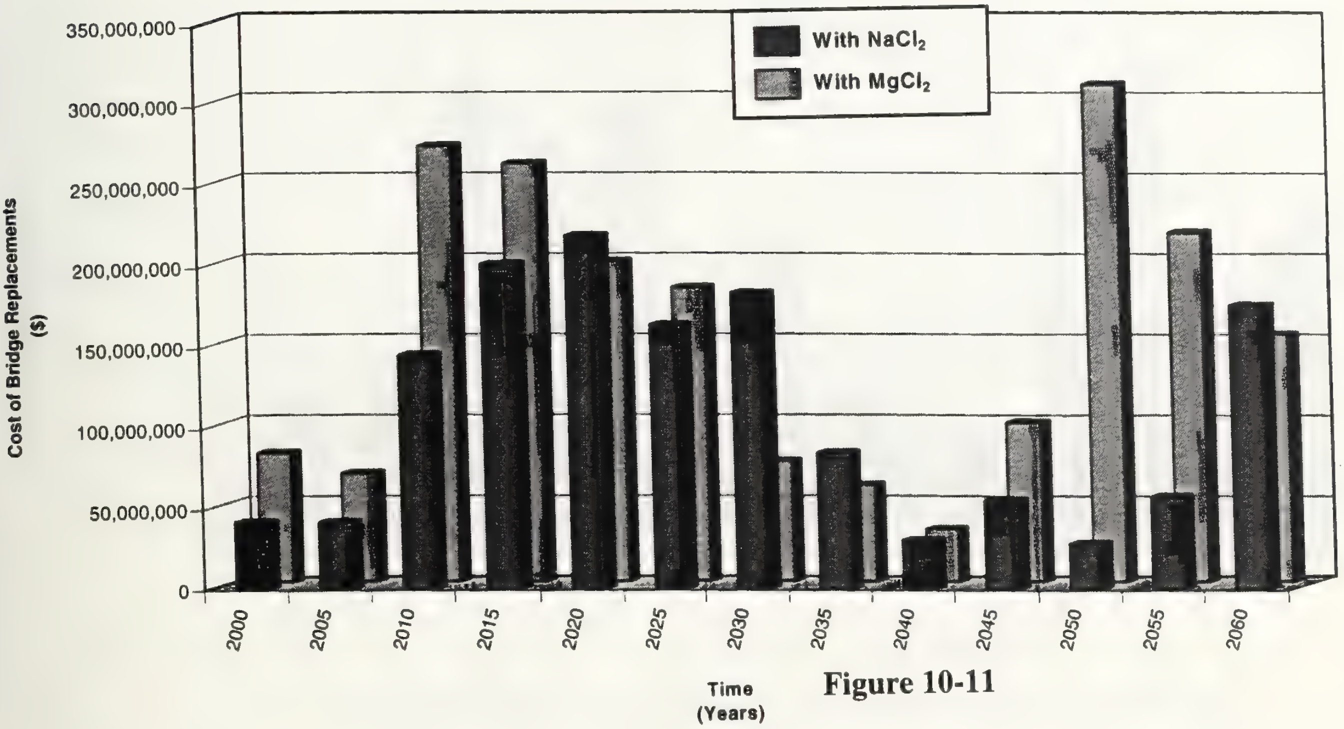


Figure 10-11

Future Bridge Replacement Required for Two Scenarios on all Presently Treated Bridges

If $MgCl_2$ Reduces Service Life by 25%

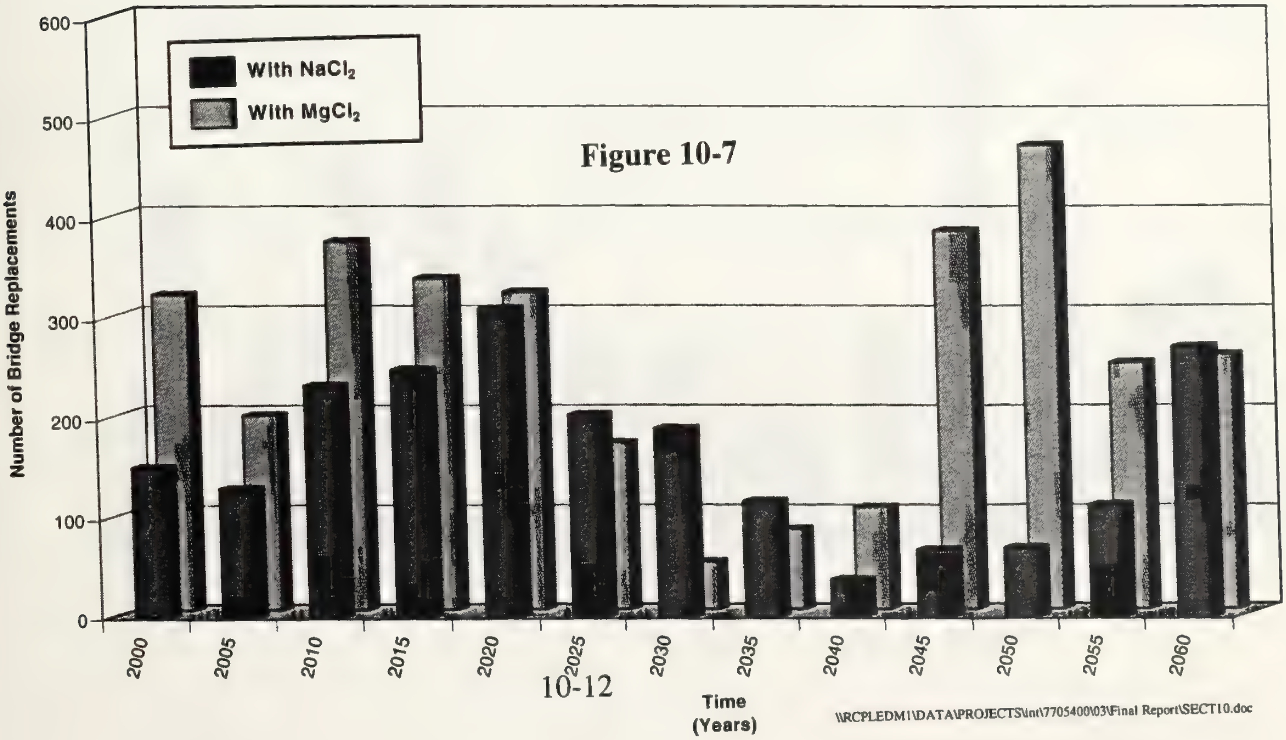


Figure 10-7

Future Bridge Replacement Needs for Two Scenarios on all Presently Treated Bridges

If $MgCl_2$ Reduces Service Life by 25%

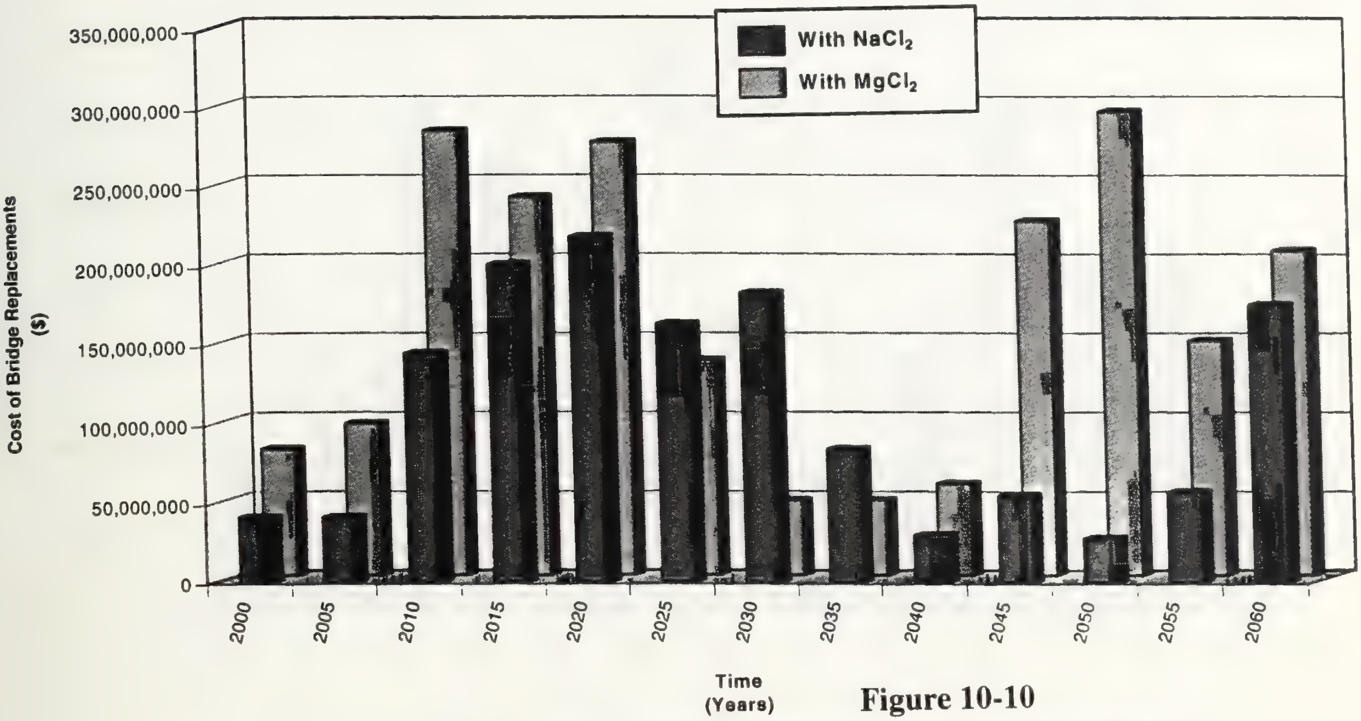


Figure 10-10

Future Bridge Replacements Required for Two Scenarios on all Presently Treated Bridges

If $MgCl_2$ Reduces Service Life by 30%

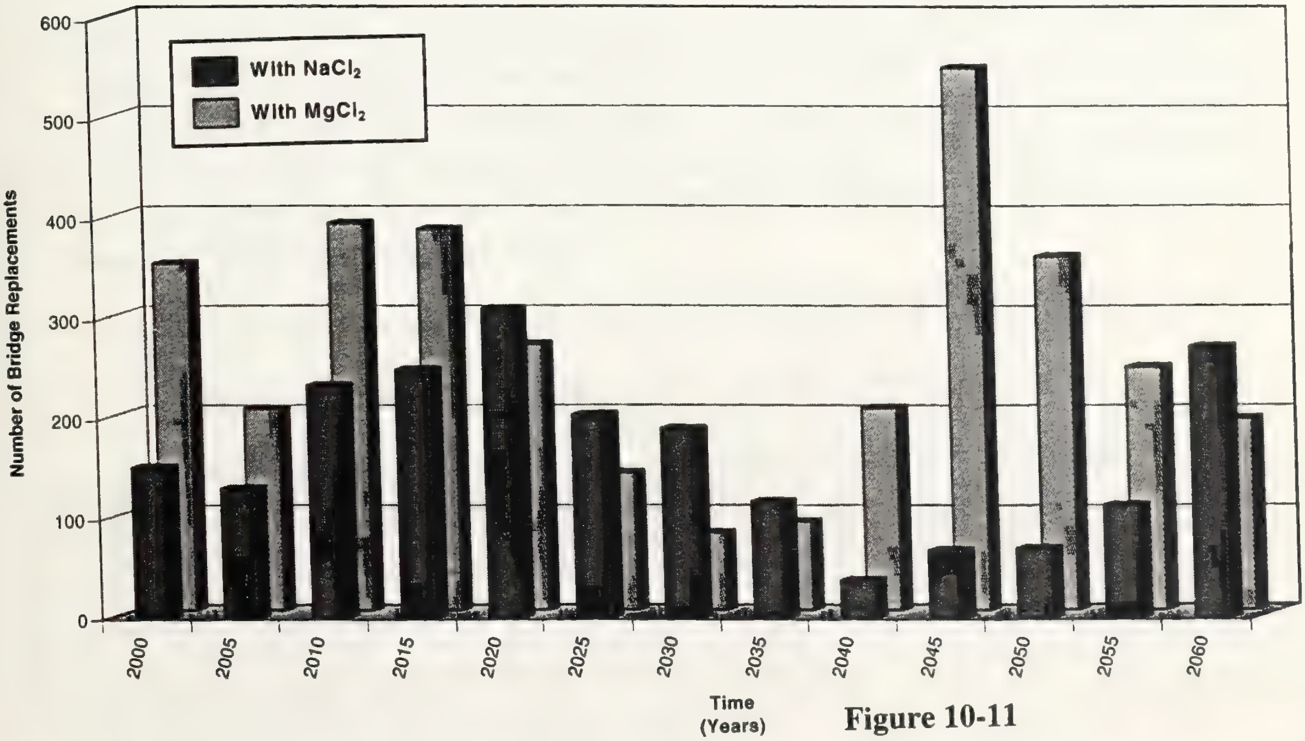
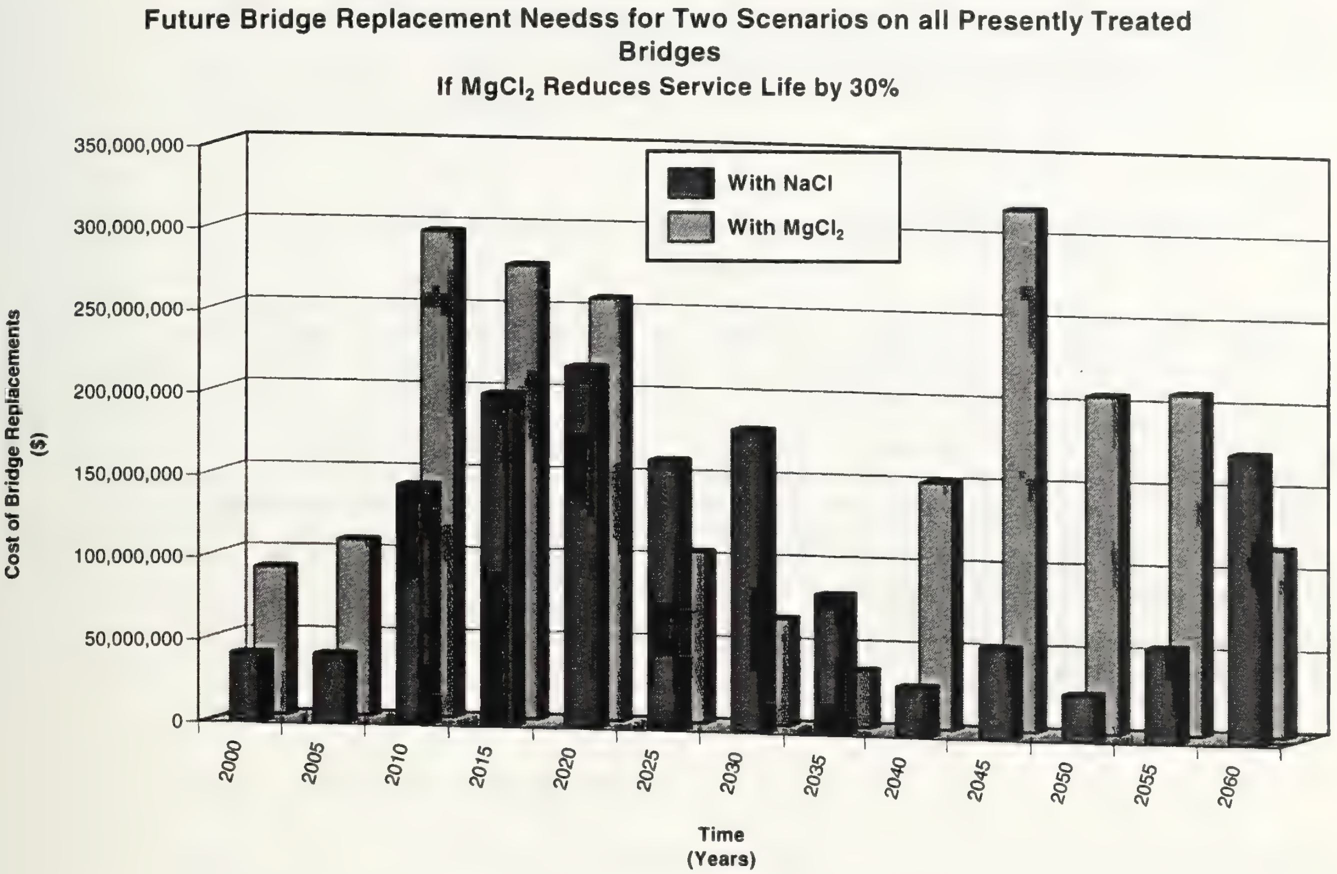


Figure 10-11



Future Bridge Replacement Needss for Two Scenarios on all Presently Treated Bridges

If $MgCl_2$ Reduces Service Life by 30%

10.5.3.2 Future Bridge Costs in Current Dollars

Results from the life cycle cost analysis are summarized in the following tables and figures. Table 10-1 summarizes the results of the life cycle cost analysis, expressed as the total amount of present dollars that are required for the entire analysis period if anti-icing policies are applied to all currently treated bridges, in the future. The analysis period has been varied from 20 to 60 years. The results are also expressed as the total cost increase due to the effects of magnesium chloride.

Table 10-2 is based on the same life cycle cost analysis that was described above for

Effect of a Complete Switch to $MgCl_2$ on Future Bridge Replacement Needs
(in todays dollars)

Variation in Effect of $MgCl_2$ on Service Life	0% (no $MgCl_2$)	20%	25%	30%
Total 20 Year Costs	$ 313,553,286	$ 461,287,320	$ 481,790,974	$ 528,965,333
Total 20 Year Cost Increase due to $MgCl_2$	0	**$ 147,734,034**	**$ 168,237,688**	**$ 215,412,047**
Total 60 Year Costs	$ 578,630,237	$ 750,191,375	$ 793,522,519	$ 851,539,506
Total 60 Year Cost Increase due to $MgCl_2$	0	**$ 171,561,138**	**$ 214,892,283**	**$ 272,909,269**

Table 10-1

Table 10-1, only the results are expressed as annuity payments, or the payments that would have to be invested annually over the analysis period to be equivalent to the present worth sum. The results are also expressed as the annual cost increase due to the effects of magnesium chloride.

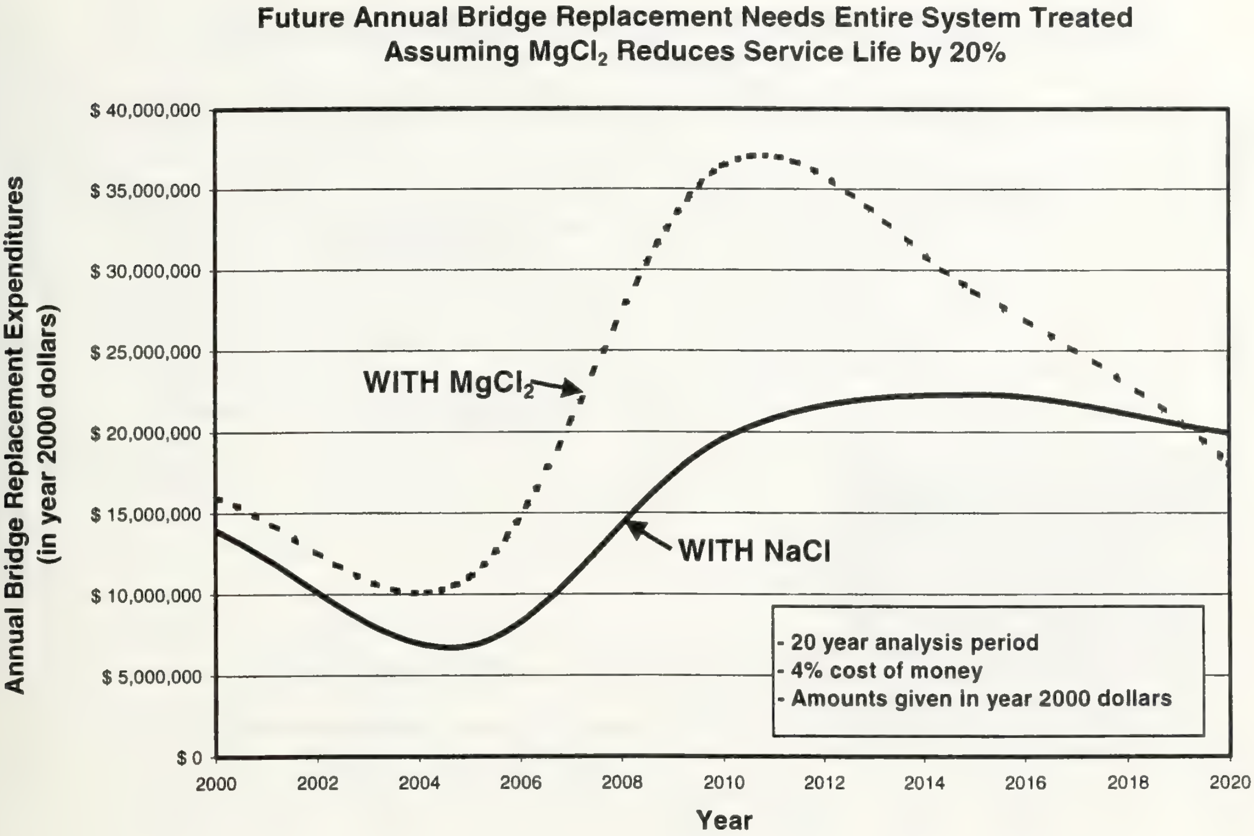
Effect of a Complete Switch to $MgCl_2$ on Future Annual Bridge Replacement Needs
(in todays dollars)

Variation in Effect of $MgCl_2$ on Service Life	0% (no $MgCl_2$)	20%	25%	30%
Average Annual Cost (20 year analysis)	$ 23,071,800	$ 33,942,328	$ 35,451,023	$ 38,922,195
Average Annual Cost Increase due to $MgCl_2$	$ 0	**$ 10,870,529**	**$ 12,379,224**	**$ 15,850,395**
Average Annual Cost (60 year analysis)	$ 25,576,524	$ 33,159,843	$ 35,075,160	$ 37,639,617
Average Annual Cost Increase due to $MgCl_2$	$ 0	**$ 7,583,319**	**$ 9,498,635**	**$ 12,063,093**

Table 10-2

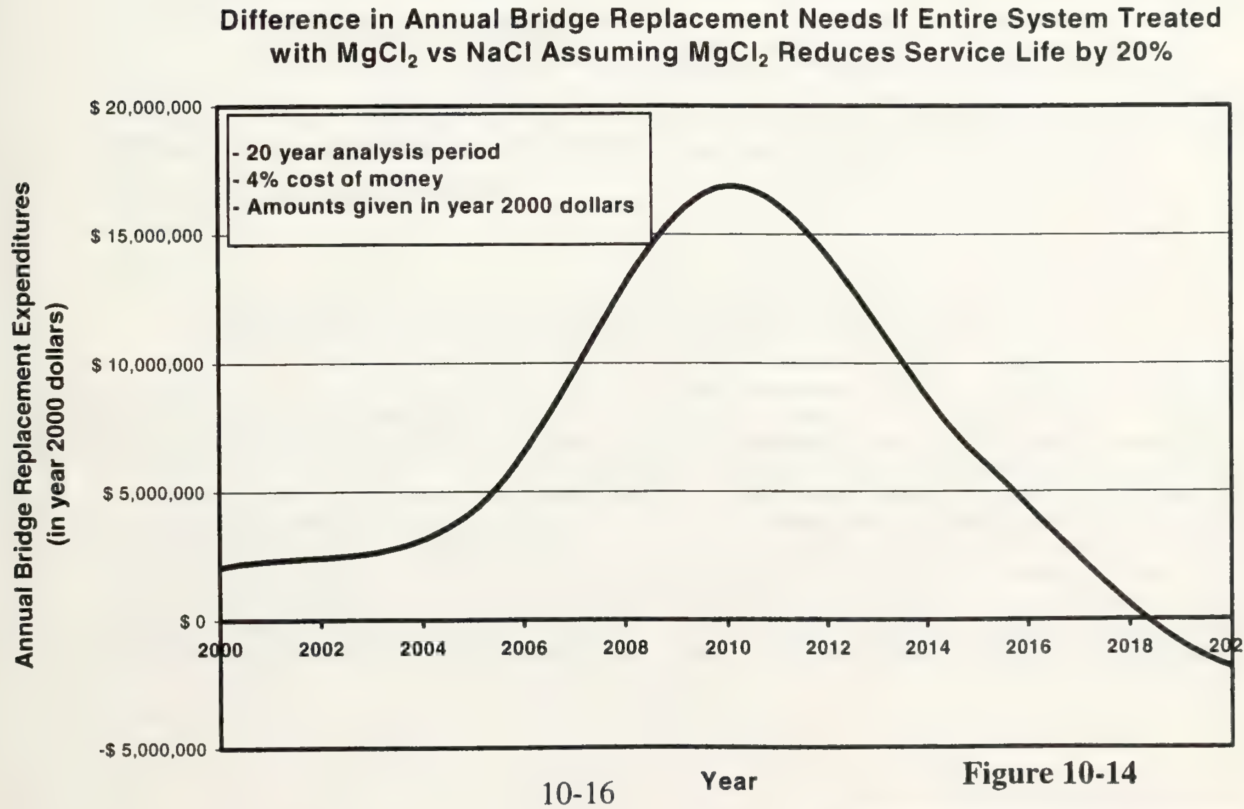
10.5.3.3 Variation in Future Needs

Figures 10-13 to 10-15 show the effect of a total switch to anti-icing with magnesium chloride will have on currently treated bridge inventory in the next twenty years with only a 20% decrease in the remaining service life of the structures. This 20% decrease is likely a conservative estimate of the accelerated deterioration caused by magnesium chloride. Figures similar to Figures 10-13 to 10-15, except with 20%, 25% and 30% decreases in the remaining bridge service lives and 20 and 60 year analysis periods can be found in Appendix C. Tables that show the life cycle cost analyses in more detail for all cases are also found in this section.



Future Annual Bridge Replacement Needs Entire System Treated Assuming $MgCl_2$ Reduces Service Life by 20%

Figure 10-13



Difference in Annual Bridge Replacement Needs If Entire System Treated with $MgCl_2$ vs NaCl Assuming $MgCl_2$ Reduces Service Life by 20%

Figure 10-14

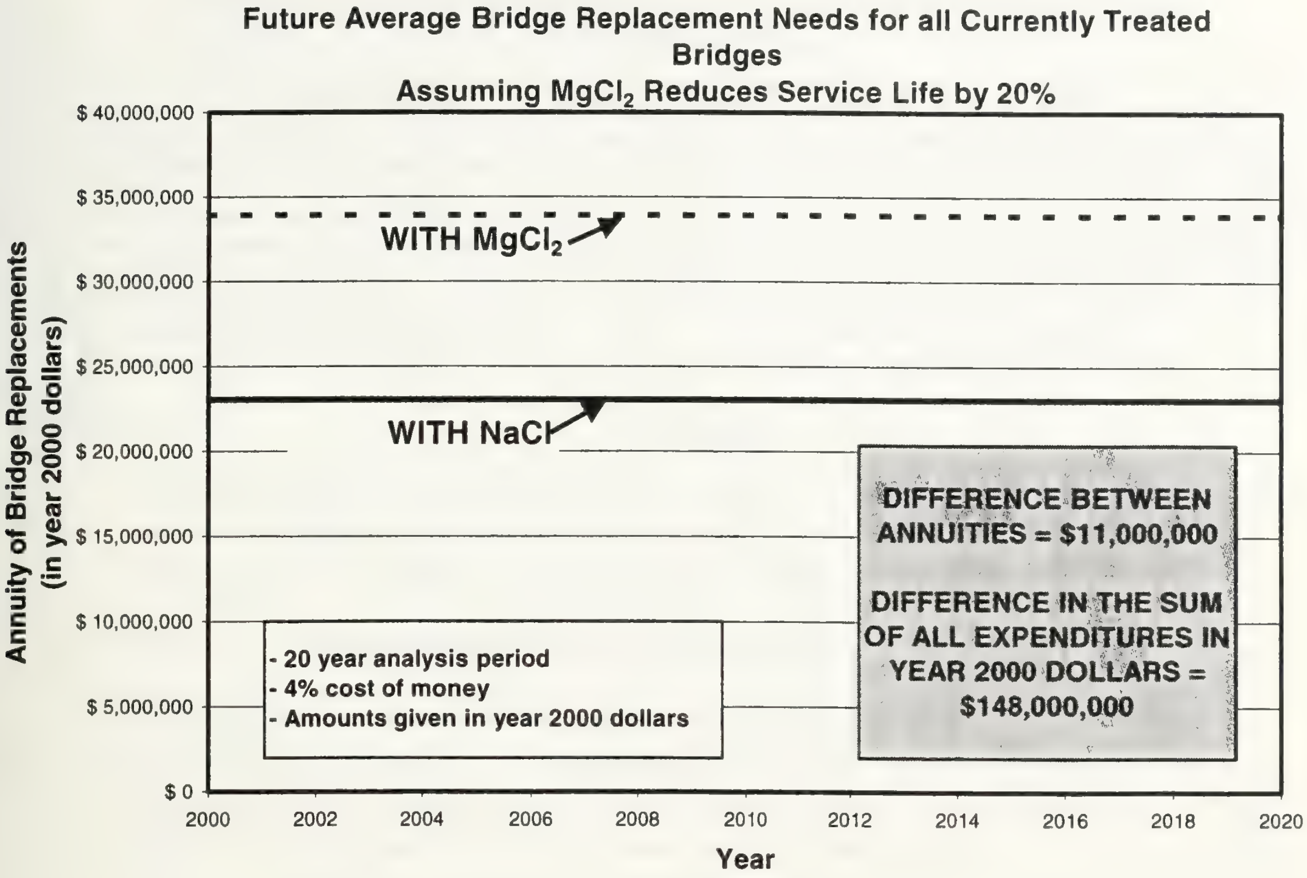


Figure 10-15

10.5.3.4 Future Costs with Inflation

Tables 10-3 and 10-4 are similar to the life cycle cost analysis summary Table 10-1 and 10-2 except the analysis include a 6% annual increase in expenditures due to rising inflation and increased standards.

Effect of a Complete Switch to $MgCl_2$ on Future Bridge Replacement Needs
(in future dollars)

Variation in Effect of $MgCl_2$ on Service Life	0% (no $MgCl_2$)	20%	25%	30%
Total 20 Year Costs	$ 565,396,849	$ 835,064,209	$ 854,282,362	$ 940,879,206
Total 20 Year Cost Increase due to $MgCl_2$	0	**$ 269,667,360**	**$ 288,885,513**	**$ 375,482,356**
Total 60 Year Costs	$ 2,125,904,855	$ 3,513,731,275	$ 3,617,946,963	$ 3,998,172,135
Total 60 Year Cost Increase due to $MgCl_2$	0	**$ 1,387,826,420**	**$ 1,492,042,108**	**$ 1,872,267,281**

Table 10-3

Effect of a Complete Switch to $MgCl_2$ on Future Annual Bridge Replacement Needs
(in future dollars)

Variation in Effect of $MgCl_2$ on Service Life	0% (no $MgCl_2$)	20%	25%	30%
Average Annual Cost (20 year analysis)	$ 22,711,943	$ 33,544,458	$ 34,316,450	$ 37,795,037
Average Annual Cost Increase due to $MgCl_2$	$ 0	**$ 10,832,515**	**$ 11,604,506**	**$ 15,083,094**
Average Annual Cost (60 year analysis)	$ 18,010,463	$ 29,767,997	$ 30,650,902	$ 33,872,133
Average Annual Cost Increase due to $MgCl_2$	$ 0	**$ 11,757,533**	**$ 12,640,439**	**$ 15,861,670**

Table 10-4

Detailed results for all of the different scenarios are included in Appendix C. This includes detailed results and charts for the life cycle cost analysis with future dollars, varying analysis periods, and varying effects of magnesium chloride.

10.5.3.5 Economic Impact from Complete Switch to $MgCl_2$

The economic impact on the MDT bridge infrastructure varies due to many factors such as analysis period, future cost of money, and effect on individual bridge service lives. The life cycle cost analysis was completed using several assumed reductions in bridge service life, 20, 25 and 30%. All of these scenarios have annual capital budgets that rise and fall. Graphs are included in Appendix C to show how the capital budget curves change shape with different assumed scenarios. When the costs are averaged, the annual budgets all show significant increases in capital budgets to cover the reduced service lives from the continued use of magnesium chloride. Overall, the effect of magnesium chloride on future capital budgets was found to be in the range of $7.5M to 15M annually.

10.5.4 Economic Impact of Magnesium Chloride Anti-icer – Second Management Scenario

The first management scenario was to examine the effect of using magnesium chloride anti-icer on all of the presently treated bridge sites in Montana. This totaled approximately 1950 bridge sites, with a replacement value of $1.3 billion. The second management scenario is to examine the economic impact of using magnesium chloride anti-icer only on the sites that are currently having magnesium chloride applied to them. The number of sites that are currently receiving magnesium chloride are significantly less that in the first scenario. There are only approximately 250 bridge sites that fall into this category, and the replacement value of these sites totals only $350M (approximately ¼ of

the bridge replacement value used in scenario 1). The site list of the scenario 2 bridges has been provided by MDT and is included in Appendix B. Also a map of Montana with all of the areas that are currently receiving the anti-icer highlighted is included in this report. The map is located in an envelope in Appendix E. The bridge sites are generally located immediately around the major centers in the State (including Great Falls, Helena, Missoula, Butte, Kalispell, Shelby, Havre, Sidney, Miles City, Billings, Bozeman, Glendive, Lewiston, and others) and along the western sections of I 90.

10.5.4.1 Application of the Life Cycle Cost Analysis to the Montana Bridge Sites that Currently Receive Magnesium Chloride Anti-icer

The expenditure amounts and bridge replacement years that were used in the life cycle cost analysis for the subset of bridges that are currently receiving magnesium chloride deicer is detailed in figures 10-16 to 10-21 that follow.

As previously described in the first management scenario, two separate analysis periods were used in the analysis of the second management scenario. A 60-year analysis period was selected in order to encompass all of the bridge replacements for these bridges as well as being consistent with the first management scenario. The second analysis period was also consistent with the first management scenario. A 20-year analysis period was used to reflect the more imminent needs in the near future.

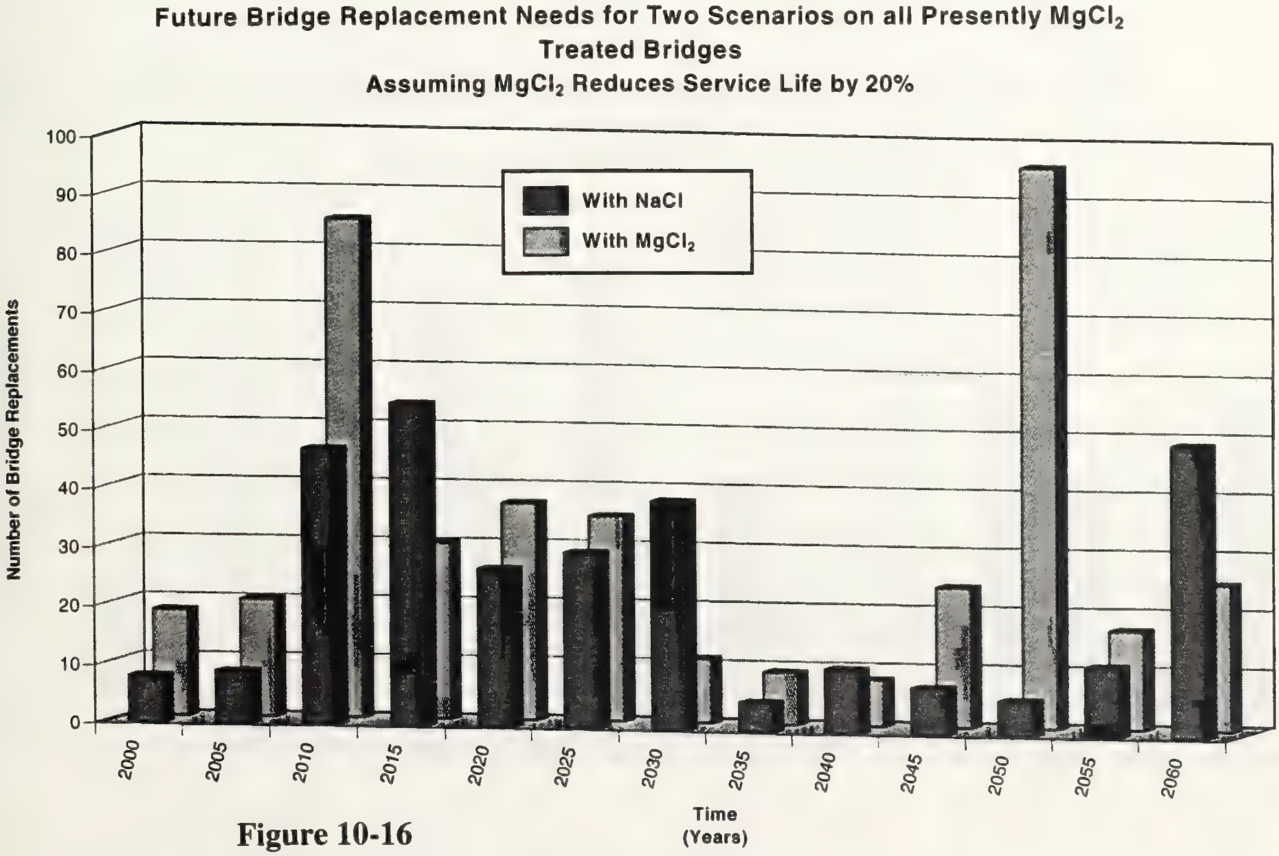


Figure 10-16

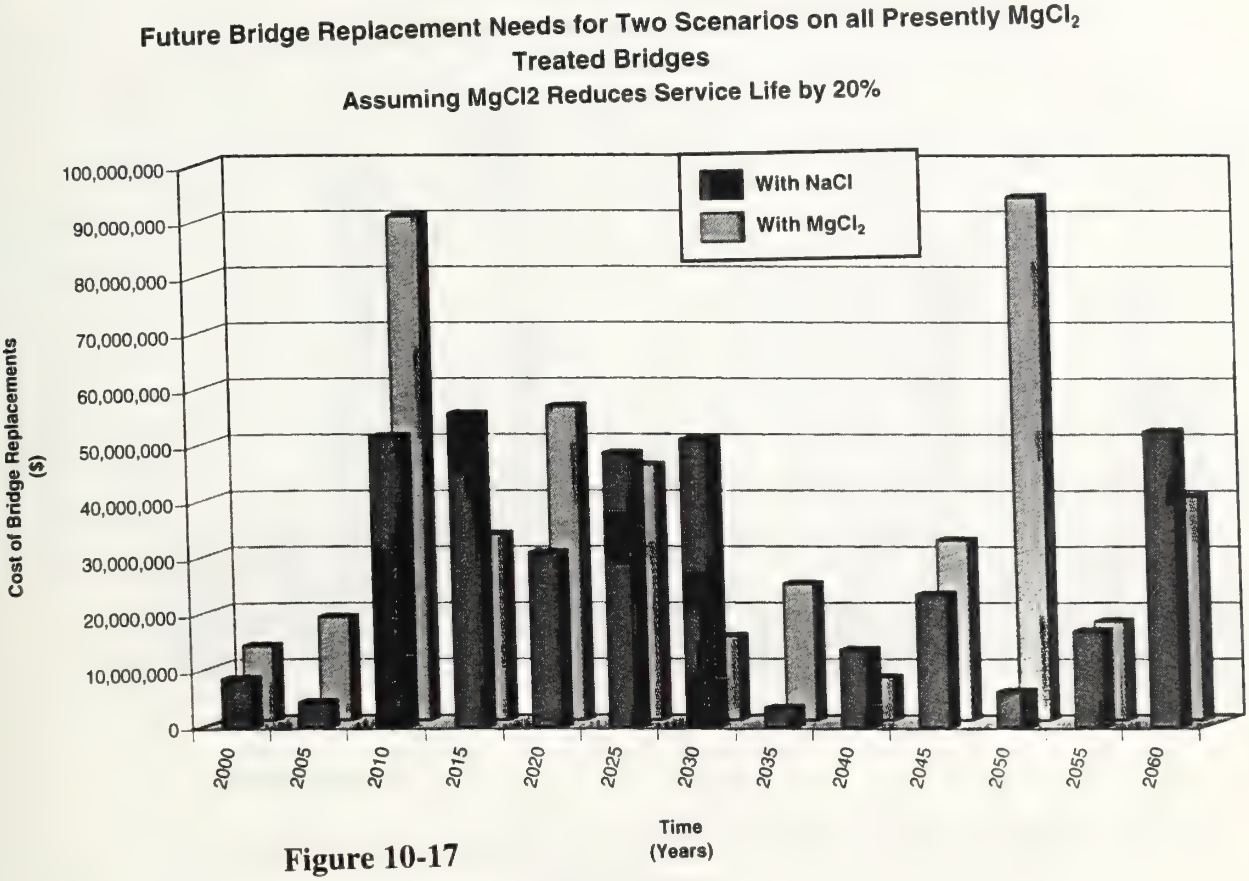


Figure 10-17

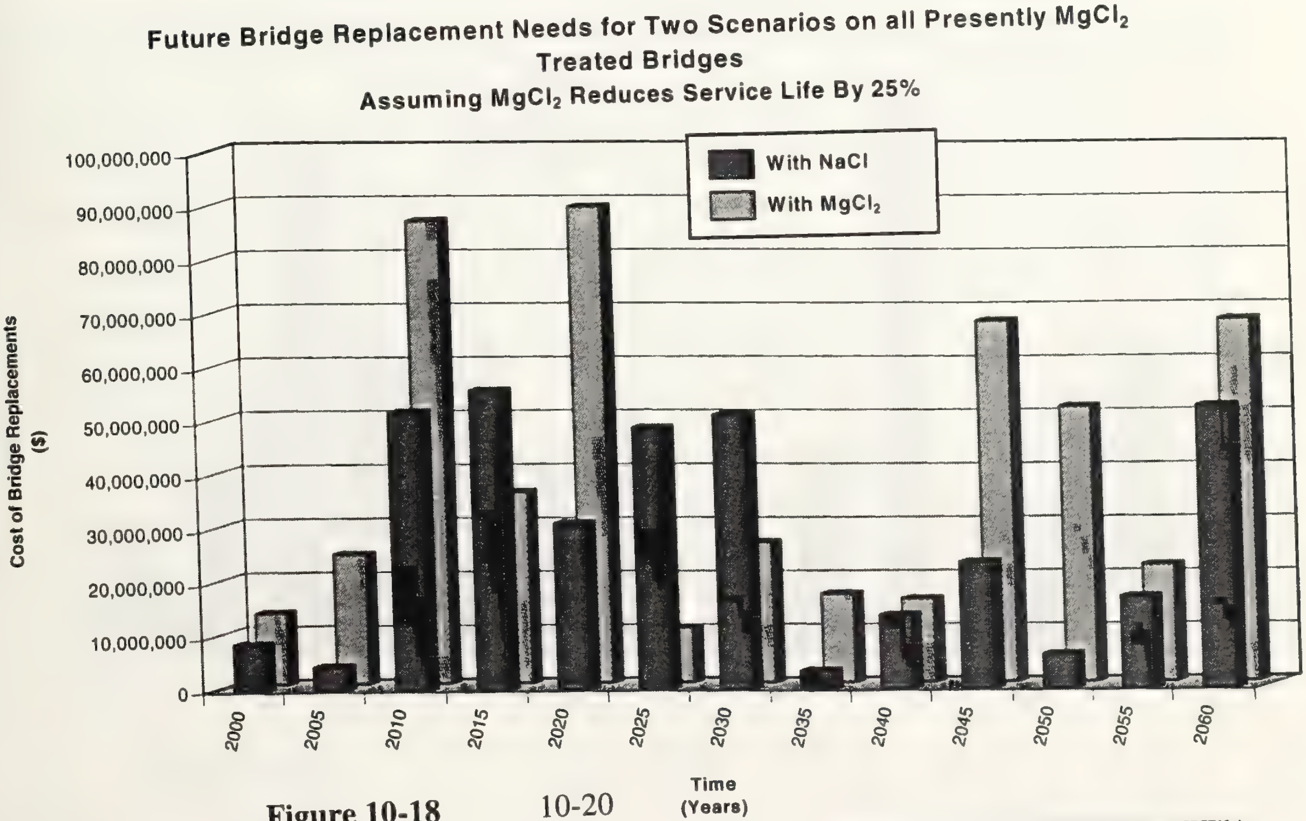


Figure 10-18

Future Bridge Replacement Needs For Two Scenarios on all Presenty $MgCl_2$ Treated Bridges

Assuming $MgCl_2$ Reduces Service Life by 25%

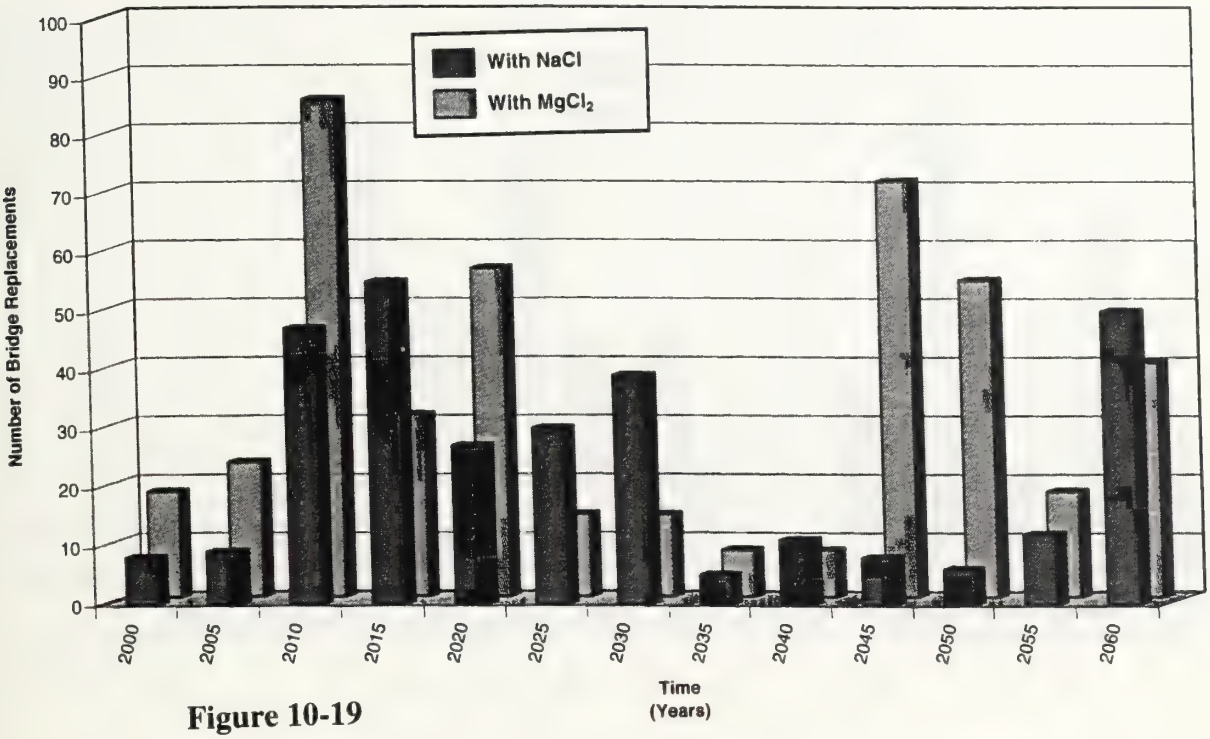


Figure 10-19

Future Bridge Replacement Needs for Two Scenarios on all Presently $MgCl_2$ Treated Bridges

Assuming $MgCl_2$ Reduces Service Life by 30%

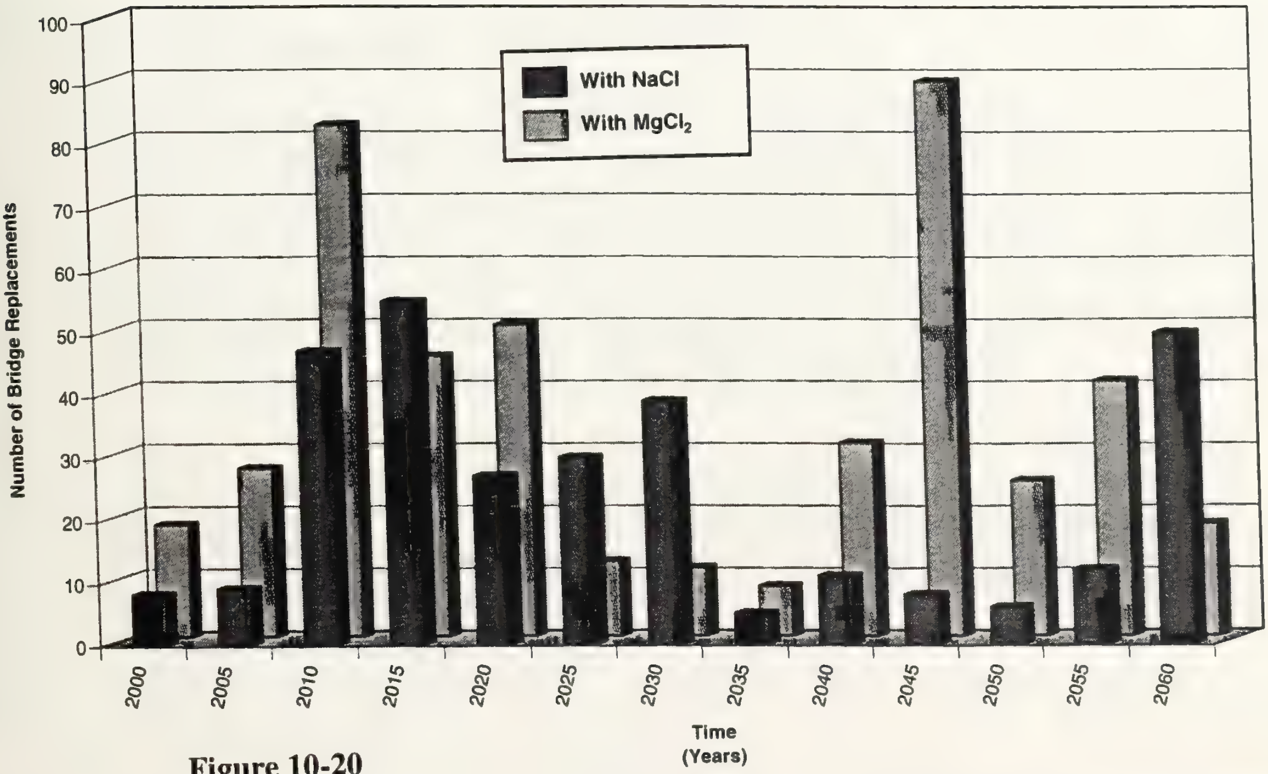


Figure 10-20

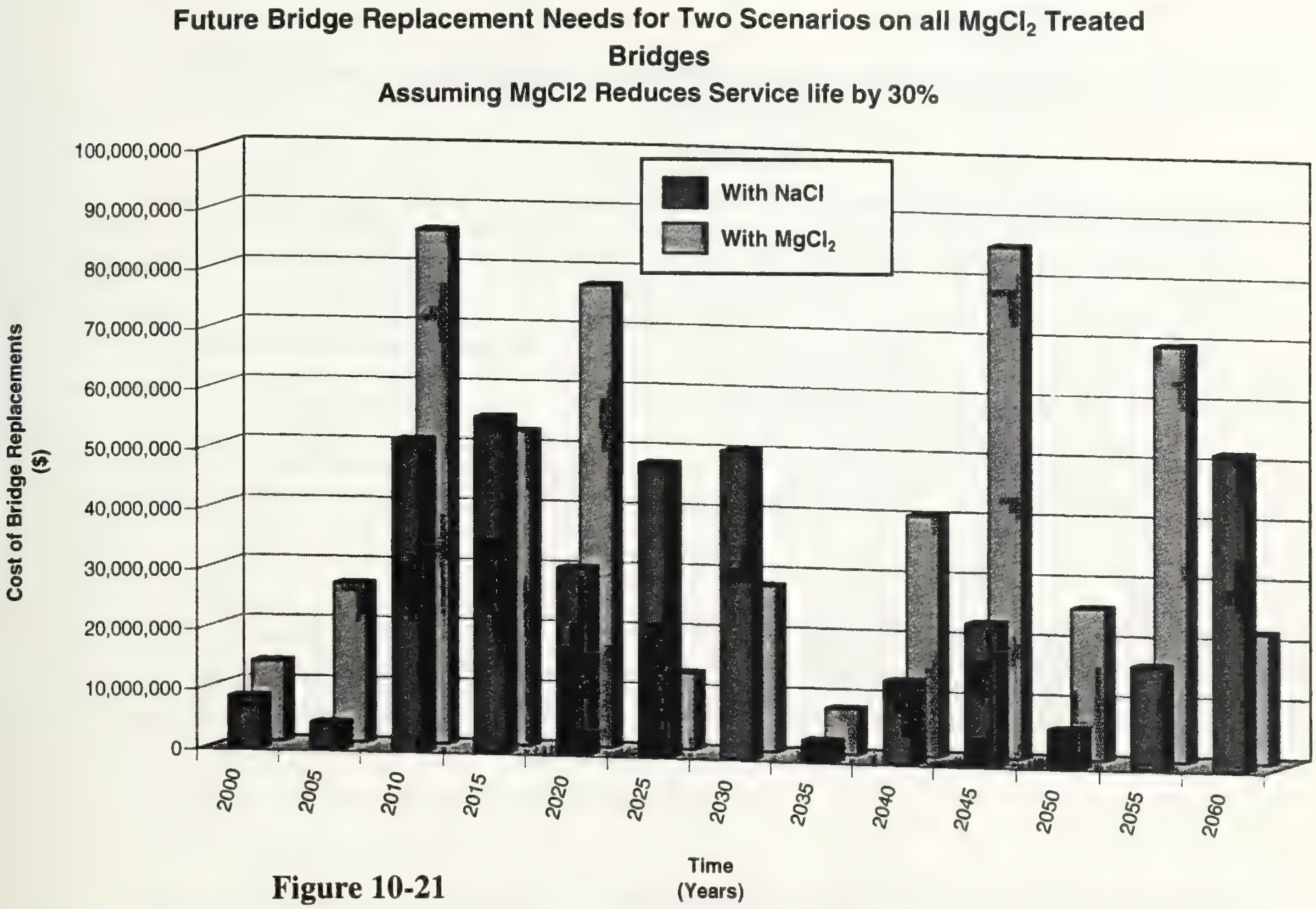


Figure 10-21

10.5.4.2 Future Bridge Costs in Current Dollars

The results from the life cycle cost analysis for the second management scenario are presented in the following tables and figures. Table 10-5 summarizes the results of the life cycle cost analysis. Again, this is expressed as the total amount of present dollars that are required for the entire analysis period, which is either 20 or 60 years. This analysis assumes that the current anti-icing policies are applied to these select bridges for the entire period. The results have also been summarized to show the total cost increase due to the effects of having magnesium chloride anti-icer applied to them.

Effect of Continued Use Of $MgCl_2$ on Future Bridge Replacement Needs for Bridges That Currently Receive $MgCl_2$
(in todays dollars)

Variation in Effect of $MgCl_2$ on Service Life	0% (no $MgCl_2$)	20%	25%	30%
Total 20 Year Costs	$ 81,277,827	$ 107,642,173	$ 111,281,543	$ 122,054,358
Total 20 Year Cost Increase due to $MgCl_2$	0	**$ 26,364,346**	**$ 30,003,716**	**$ 40,776,531**
Total 60 Year Costs	$ 139,810,107	$ 183,269,602	$ 192,489,110	$ 207,106,602
Total 60 Year Cost Increase due to $MgCl_2$	0	**$ 43,459,495**	**$ 52,679,003**	**$ 67,296,495**

Table 10-5

Table 10-6 that follows is based on the same cost analysis data as in Table 10-4, with the results expressed as annuity payments. Recall that annuity payments are the amount that would have to be invested annually for the entire analysis period in order to be equivalent to the present worth sum. The results have also been expressed as the annual cost increase due to the effects of magnesium chloride.

Effect of Continued Use Of $MgCl_2$ on Future Annual Bridge Replacement Needs for Bridges That Currently Receive $MgCl_2$
(in todays dollars)

Variation in Effect of $MgCl_2$ on Service Life	0% (no $MgCl_2$)	20%	25%	30%
Average Annual Cost (20 year analysis)	$ 5,980,565	$ 7,920,500	$ 8,188,291	$ 8,980,973
Average Annual Cost Increase due to $MgCl_2$	$ 0	**$ 1,939,935**	**$ 2,207,726**	**$ 3,000,409**
Average Annual Cost (60 year analysis)	$ 6,179,865	$ 8,100,855	$ 8,508,374	$ 9,154,494
Average Annual Cost Increase due to $MgCl_2$	$ 0	**$ 1,920,990**	**$ 2,328,509**	**$ 2,974,629**

Table 10-6

10.5.4.3 Variation in Future Needs for the Second Management Scenario

Figures 10-22 to 10-24 that follow, show the effect that magnesium chloride will have on the bridge sites that are currently treated with magnesium chloride anti-icer. These figures represent a 20-year analysis, with only a 20% decrease in the remaining service life of the structures. Again, this 20% decrease in service life is likely a conservative estimate of the accelerated deterioration caused by magnesium chloride. Figures tha are similar to Figures 10-22 to 10-24 except with 20%, 25%, and 30% decreases in the

remaining bridge service lives and 20 and 60-year analysis periods are located in Appendix C. Additional tables that detail the life cycle cost analyses for all cases described above are also located in this Appendix C.

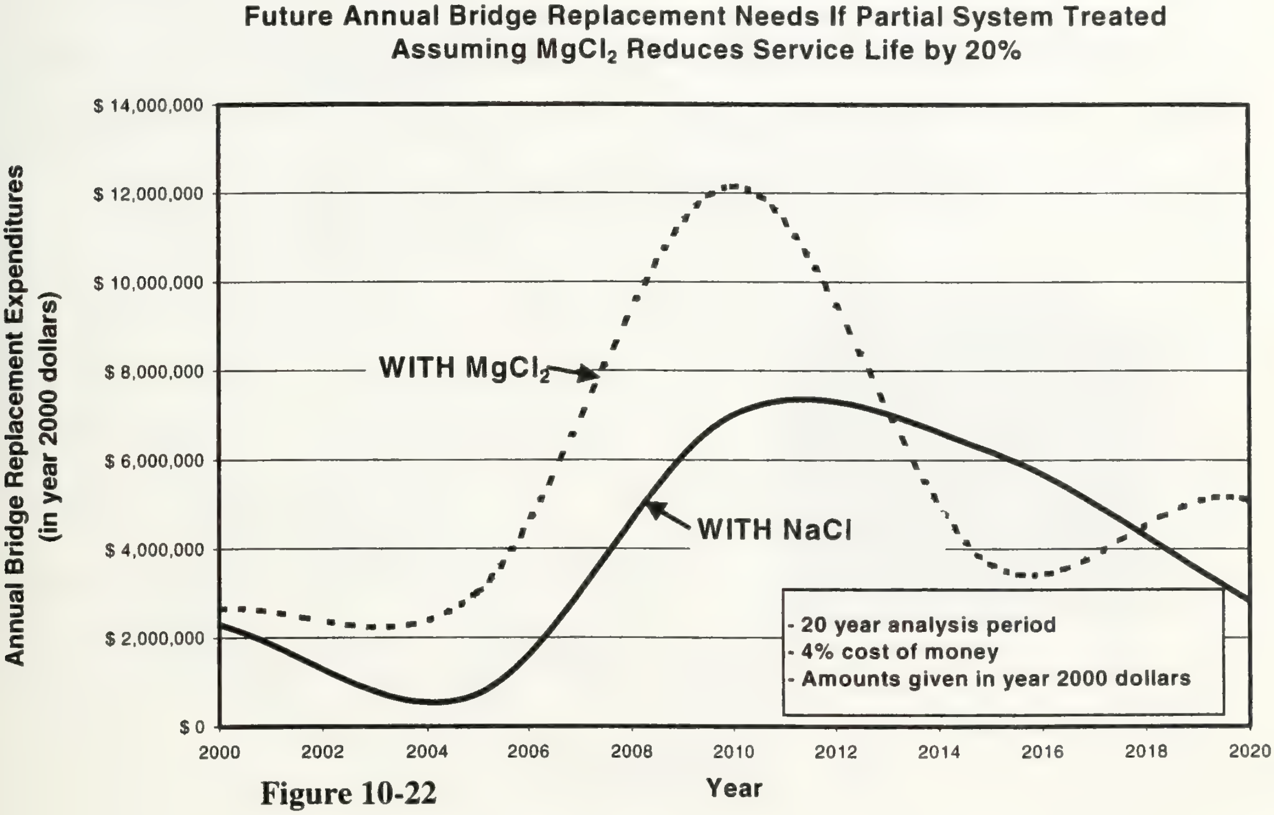


Figure 10-22

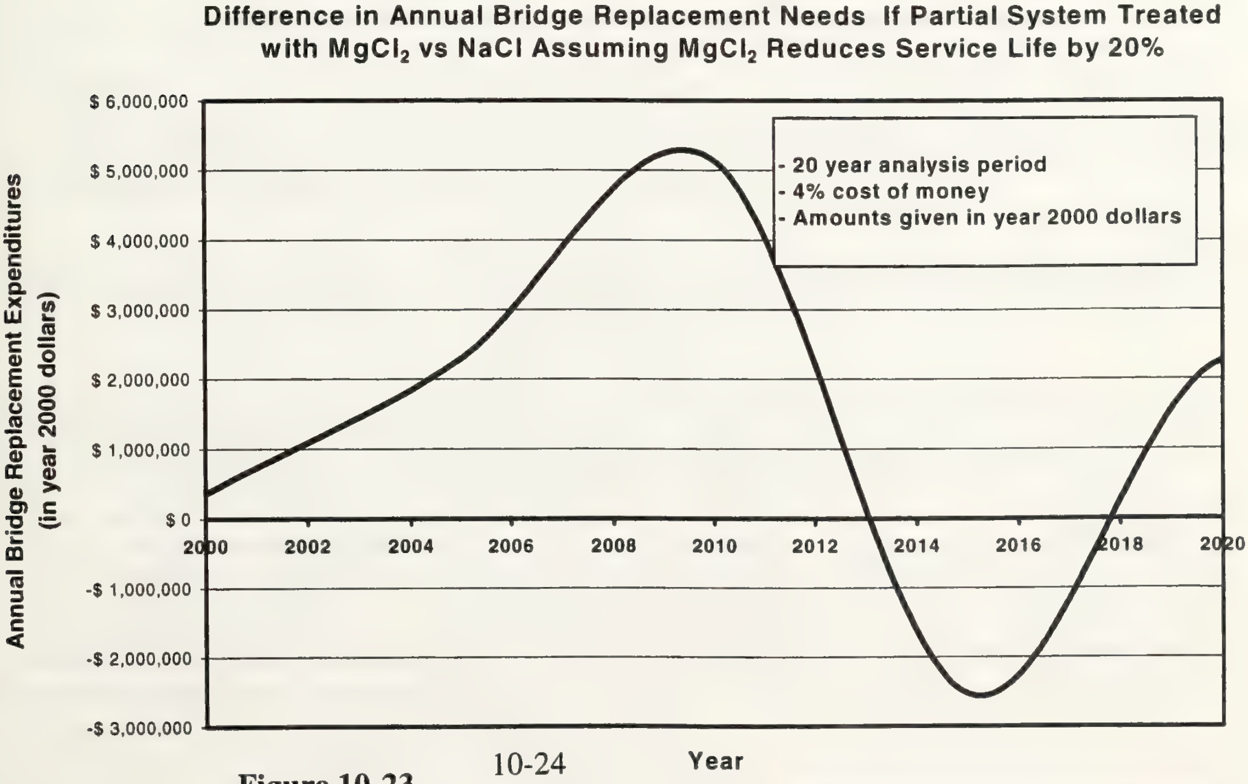
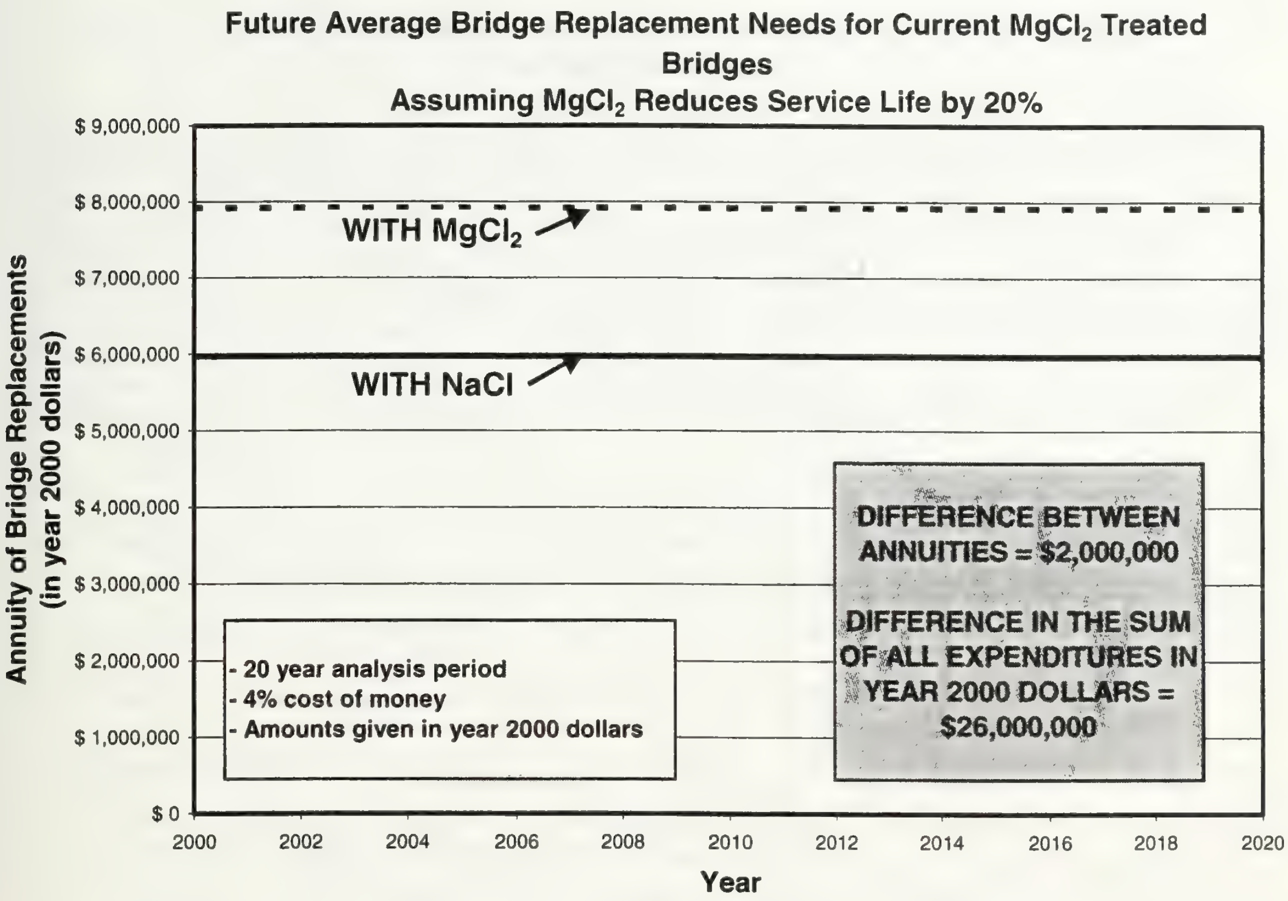


Figure 10-23



Future Average Bridge Replacement Needs for Current $MgCl_2$ Treated Bridges
Assuming $MgCl_2$ Reduces Service Life by 20%

Figure 10-24

10.5.4.4 Future Costs with Inflation for the Second Management Scenario

Tables 10-7 and 10-8 are similar to the life cycle cost analysis summary Table 10-5 except the analysis includes a 6% annual increase in expenditures due to rising inflation and increased standards for the replacement bridges.

Effect of Continued Use Of $MgCl_2$ on Future Bridge Replacement Needs for Bridges That Currently Receive $MgCl_2$
(in future dollars)

Variation in Effect of $MgCl_2$ on Service Life	0% (no $MgCl_2$)	20%	25%	30%
Total 20 Year Costs	$ 155,642,896	$ 188,693,503	$ 193,965,661	$ 218,429,101
Total 20 Year Cost Increase due to $MgCl_2$	0	**$ 33,050,607**	**$ 38,322,765**	**$ 62,786,206**
Total 60 Year Costs	$ 531,758,250	$ 831,577,840	$ 835,489,817	$ 1,003,906,122
Total 60 Year Cost Increase due to $MgCl_2$	0	**$ 299,819,590**	**$ 303,731,567**	**$ 472,147,872**

Table 10-7

Effect of Continued Use Of $MgCl_2$ on Future Annual Bridge Replacement Needs for Bridges That Currently Receive $MgCl_2$
(in future dollars)

Variation in Effect of $MgCl_2$ on Service Life	0% (no $MgCl_2$)	20%	25%	30%
Average Annual Cost (20 year analysis)	$ 6,252,162	$ 7,579,802	$ 7,791,584	$ 8,774,278
Average Annual Cost Increase due to $MgCl_2$	$ 0	**$ 1,327,640**	**$ 1,539,422**	**$ 2,522,117**
Average Annual Cost (60 year analysis)	$ 4,505,005	$ 7,045,048	$ 7,078,190	$ 8,504,997
Average Annual Cost Increase due to $MgCl_2$	$ 0	**$ 2,540,043**	**$ 2,573,185**	**$ 3,999,992**

Table 10-8

Detailed results for all of the different scenarios are included in Appendix C. This includes detailed results and charts for the life cycle cost analysis with future dollars, varying analysis periods, and varying effects of magnesium chloride.

10.5.4.5 Economic Impact From a Continued Use of $MgCl_2$

Just as the economic impact of using receiving magnesium chloride varied due to many various factors, the economic impact on the 250 MDT bridge sites that are currently receiving magnesium chloride anti-icer varies as well. These variations are due to many factors such as the analysis period, future cost of money, and effect on individual bridge service lives. The life cycle cost analysis was completed using several assumed reductions in bridge service life, 20, 25 and 30%. All of these scenarios have annual capital budgets that rise and fall. Graphs are included in Appendix C to show how the capital budget curves change shape with different assumed scenarios. When the costs are averaged, the annual budgets all show significant increases in capital budgets to cover the reduced service lives from the continued use of magnesium chloride. Overall, the effect of magnesium chloride on future capital budgets was found to be in the range of $2M to 3M annually. This is an increase of 30 to 50% over the cost of managing these bridge sites if only sodium chloride deicer had been applied. These numbers are of course expected to increase if magnesium chloride anti-icer is applied to an increased number of bridge sites.

SECTION 11.0

CONCLUSIONS

SECTION 11 CONCLUSIONS

11.1 GENERAL

This project involved a limited study of the corrosion effects and economic impact of bare pavement policy using magnesium versus sodium chloride on Montana bridges. Since there are many possible economic and safety-related benefits from using magnesium chloride anti-icing practice, this study provides only one side of the total picture. MDT has well established purchasing requirements with stringent approval tests for chemicals used in deicing and anti-icing, but the tests do not currently include any that measure the impact on concrete surfaces or corrosion of reinforced concrete.

Chloride ions penetrate reinforced concrete and induce corrosion damage in a manner that is entirely different from the corrosion of exposed steel surfaces. Magnesium chloride contains two chloride ions for each molecule while sodium chloride contains one. Previous tests by MDT's bridge staff had reported very high chloride contents on Montana bridges treated with magnesium chloride. Additional chloride tests were done as part of this study to verify the previously reported high chloride contents.

A total of twenty Montana bridges were field tested, ten bridges on a stretch of Interstate 90 that had been treated primarily with magnesium chloride anti-icing and another ten with conventional sodium chloride deicing over the past ten years. Four hundred total samples were taken for chloride tests. The bridges were on adjacent sections of Interstate 90, so the traffic counts and many other site related variables were similar.

Rather than take totally random test samples, they were taken from representative locations, half from the right traffic lane wheel path and the other half from the right shoulder location near the gutter-line. The tests at each location were carefully located to represent three depths from the surface. The test data was used to investigate the relevant chloride diffusion parameters that relate to bridge service life. SHRP procedures involving Fick's Second Law of Diffusion were used for analysis. The chloride parameters were used to find the affect on bridge service life for magnesium chloride compared to sodium chloride deicer.

Two possible pavement management scenarios were investigated by cost analysis for their impact on bridges. Their cost impacts were compared with the control scenario of using conventional deicing practice with sodium chloride. The first pavement

management scenario involved a hypothetical situation in which the two-thirds of Montana bridges currently expected to need regular deicing during their service lives are treated from this point on with magnesium chloride. The second management scenario involved the bridge costs resulting from continuing the current MDT policy of only treating certain locations with magnesium chloride while predominantly using conventional sodium chloride deicer. A conservative approach was taken throughout the analysis, and the conclusions regarding the impact of magnesium chloride on bridges are believed to be conservative.

11.1.1 Chloride Data Analysis Conclusions

- 243% higher chloride contents were found in the wheel path test locations as compared to the shoulder locations. The finding was consistent at all test depths regardless of which chemical treatment had been used.

- For four of the six chloride data sets taken on or off the wheel paths and at three different depths, the magnesium chloride exposed bridges had slightly higher chloride contents than the sodium chloride treated sites. The differences were not statistically significant, and could be explained by the range in standard deviation.

- For the deeper wheel path data sets the differences in chlorides were significantly higher for the magnesium chloride treated decks. The data showed a trend to greater difference with deeper depth from the surface.

- Magnesium chloride–treated decks had 78% (1.42 lb/yd^3) higher chloride contents than sodium chloride-treated decks at 1.5 inch below surface depths in the wheel paths. The data ranged from 31 to 125% (0.56 to 2.28 lb/yd^3) higher for magnesium chloride.

- At 2.25-inch depth below surface in the wheel paths, the chlorides averaged 185% higher for the magnesium chloride-treated decks.

- Chloride diffusion coefficients were calculated and averaged for each deck. The magnesium chloride-treated decks had 120% (0.048 in^2/yr) higher diffusion coefficients than the sodium chloride-treated decks tested in wheel path locations. The data ranged from 60 to 180% (0.024 to 0.072 in^2/yr) higher for magnesium chloride-treated decks than for sodium chloride-treated decks.

- Magnesium chloride diffuses more quickly through concrete than sodium chloride. This may be the result of its hygroscopic nature. By attracting and retaining moisture in concrete, it increases the speed of chloride migration.

11.1.2 Bridge Service Life Conclusions

- Magnesium chloride anti-icing will initiate corrosion of reinforcing steel on new unprotected decks ten to fifteen years sooner than sodium chloride deicers. The reduction in time to corrosion depends on factors such as rebar cover depth, concrete diffusion coefficient, and others.

- The bridge service life of magnesium chloride-treated bridges will be less than that of bridges exposed to sodium chloride deicer. The amount depends on such factors as reinforcing steel cover depth and bridge age when first treated with magnesium chloride.

- Depending on bridge age, cover depth, amount of deicing, and other factors, the use of magnesium chloride will reduce the service life of new bridges by 20 to 30% and the remaining service life of old bridges by the same percentage.

- The amount of life reduction will be greater on new bridges with high rebar cover than older ones with poor cover. For example, a bridge having ten years of remaining life with conventional deicing would have a service life reduction of only two to three years when deicing was replaced with magnesium chloride anti-icing, while a new bridge would have a reduction in service life of ten to twenty years.

11.1.3 Economic Analysis Conclusions

11.1.3.1 Conclusions Regarding Conventional Deicing Practice

If the portion of Montana bridges that need deicing are conventionally deiced with sodium chloride,

- the long term average annual budget needed for bridge replacement to maintain the current level of service will be in the range of $24Million. In shorter analysis periods the budgets will be less, and they will fluctuate over time.

- For group of ~250 heavily treated bridges, the average annual bridge replacement needs for the next thirty-plus years will be approximately $12Million.

- A significant increase in annual bridge replacement needs can be expected during the next twenty years, largely due to the aging of the Interstate bridges, which were constructed over a limited time period.

- For the group of moderately chemically treated bridges the average annual bridge replacement needs for the next thirty plus years is expected to be approximately $9Million.

11.1.3.2 Increased Costs If Entire System Switched to Anti-Icing

If the portion of Montana bridges that need deicing are switched to anti-icing practice the following increased bridge replacement budgets will be needed:

- Annual $10.9Million in today's dollars over the next 20 years.
- Total $148Million in today's dollars over the next 20 years.
- Total $270Million in future inflated dollars over the next 20 years.

11.1.3.3 Increased Costs from Limited Magnesium Chloride Anti-Icing

If the current anti-icing practice of treating only some roads with magnesium chloride is continued, the following increases in bridge replacement needs will result:

- the long-term average annual budget needed for bridge replacement to maintain the current level of service will be in the range of $2Million (today's dollars).

11.1.4 Effectiveness of Previous Deck Repairs

- Analysis of chloride profiles taken on the two 1993 epoxy overlays showed that the increase in deck service life will likely range from 12 to 29 years. The effectiveness of epoxy overlay will be greater when applied as a protection system prior to the development of substantial corrosion and damage.
- Analysis of chloride profiles taken on a 1993 latex-modified concrete overlay showed an expected increase in deck service life of about 29 years.

11.2 DISCUSSION FROM CONCLUSIONS

Some conclusions require additional discussion.

11.2.1 Observed Effects in Wheel Paths

Assuming the width of an average wheel path as three feet, and two wheel paths per lane, the typical bridge deck surface has about 40% of its area in the wheel paths. The increased rate of chloride diffusion in the wheel path areas is significant in its impact on the bridge deck service life. Corrosion induced potholes in the gutters do not have

to be immediately repaired. Potholes and damage located in the wheel paths must receive immediate attention to protect public safety. Such repairs are extremely expensive.

11.2.1.1 Possible Causes of Wheel Path Effects

There are several possible reasons why chlorides would penetrate more quickly through concrete in the wheel paths. Reasons affecting the chloride diffusion rate include the following:

- Fluid pumping action caused by tire pressure on wet road surfaces,
- Extra moisture in the wheel paths carried by tires. Moisture is known to increase rate of diffusion,
- Tire friction keeps the wheel paths warmer than the adjacent concrete, and temperature increases rate of diffusion.

Possible causes of increased chloride content in wheel paths include:

- Continual replenishment of surface chlorides in the wheel paths due to tracking by tires from the treated approach roads,
- Studded snow tires wear away the concrete surface, exposing capillaries to allow increased absorption of chlorides.

11.2.1.2 Heavier Chemical Treatment of Saltese Bridges

Interstate 90 in the Saltese District has higher snowfall, moisture and anti-icing application than in the Superior District. Does this account for the higher chlorides found in the Saltese District?

Had the chlorides been sampled randomly on the twenty decks, the above question would likely have been answered affirmatively. By chance, the tests were taken half in the wheel path and half near the gutter-line. The gutter-line data shows similar chlorides for both the Saltese and Superior Districts. Higher moisture levels in the Saltese District may account for reduced chloride absorption rates due to less capillary suction at the bridge deck surface. The increased chlorides occur in the wheel path areas, the worst area on a bridge deck in terms of its impact on service life.

11.2.2 Long Term Bridge Management Budget Implications

The cost analysis predicts an increase in the MDT annual budget due to use of magnesium chloride anti-icers. This increase is likely to occur over a period of time as the increased needs caused by deterioration begin to be obvious. Initially, the overall level of service of the bridge system will gradually fall until the needs become apparent.

Another interesting trend was observed during the course of this study. This trend will create the need for increased budgets due to replacement and rehabilitation of the Interstate bridges. The oldest 'baby boomer' bridges are now approaching the ends of their service lives. The data shows the trend towards increased budgets is likely to begin soon and continue for about twenty years.

11.2.3 Effectiveness of Deck Repairs

The chloride profiles showed the deck repairs to be performing well in terms of slowing the ingress of chlorides. This will result in increased service life. The amount of service life extension for any particular site will depend on factors such as the repair method selected, the timing of the repair, and the quality of the work. For example, latex overlays done on heavily salt contaminated decks will provide longer service lives if the amount of concrete removed is based on measured chloride levels. Leaving too much chloride in the deck will shorten the life of the repair. Another example is that epoxy overlays are preventive in nature and work much better if done prior to too much chloride ingress. If an epoxy overlay is applied after too much chloride has been absorbed the effect is the same as just covering up the problem, which festers away independently of the repair.

SECTION 12.0

RECOMMENDATIONS

SECTION 12 RECOMMENDATIONS

12.1 RECOMMENDATIONS FOR FURTHER ACTION

It is recommended that MDT consider the following:

- Conduct a further study to quantify to quantify the user benefits of magnesium chloride use. This will provide a more complete picture from which to make future decisions regarding further development of anti-icing practice.

- Revise the product approval method to include the following:

  1. Compatibility With Metals in Concrete (SHRP H-205.12)

  2. Compatibility With Concrete and Nonmetals (SHRP H-205.8 and H-205.9)

- Organic corrosion inhibitor research is needed to investigate corrosion protection performance in reinforced concrete:

  1. Do they prevent corrosion (SHRP H-205.12)?

  2. Can they migrate through concrete?

  3. Are the acidic ones effective in normal concrete, which is highly alkaline?

  4. Do they migrate through concrete as fast as magnesium chloride?

- Use the chloride test data and other information of this report as a baseline for future comparison of chloride penetration and absorption with time.

- Revise routine chloride sampling procedures to consider the findings on chloride build-up in wheel path versus non-wheel path. Record future test locations with respect to edge distance and wheel path location. Should future chloride testing be done only in wheel paths, since this will reduce the test data scatter, and the wheel paths are the critical areas where corrosion damage has a greater impact on the deck service life?

- Review previous MDT chloride bridge deck test data for comparison with the findings of this report.

- Set up a bridge chloride database to record future data. Select and test representative new bridges for magnesium chloride's effect on reinforced concrete. Document all relevant parameters influencing chloride ingress, such as types of deicer, application amount and year, location of test within the deck cross section, concrete and weather parameters.

- Use Copper Sulfate Electrode (ASTM C-876) tests on the same twenty Interstate 90 bridges involved in this study to confirm the study findings.

- Investigate the following:

    1. Should future chloride testing be done only in wheel paths, since this will reduce the test data scatter, and the wheel paths are the critical areas where corrosion damage has a greater impact on the deck service life?

    2. Will the impact of magnesium chloride to new bridges be greater than the impact on older bridges where sodium chloride was used for many years?

    3. Does anti-icing result in increased chloride absorption compared to deicing?

    4. How does ambient moisture level (rainfall) affect the rate of chloride absorption into concrete?

SECTION 13.0

ACKNOWLEDGEMENTS

SECTION 13 ACKNOWLEDGEMENTS

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- Mr. Reg Quinton, Acting Director, Bridge Engineering Section, Alberta Infrastructure

APPENDIX A
DATA ANALYSIS

APPENDIX A - DATA ANALYSIS METHODOLOGY

1.0 STATISTICAL ANALYSIS OF CHLORIDES AND DIFFUSION COEFFICIENTS

The goal of the statistical analysis of the chloride data and diffusion coefficients was to determine the statistical difference between these variables in bridges that have been exposed to magnesium chloride deicer and bridges that have been exposed to sodium chloride deicer. The analysis was first performed on the measured chloride data followed by the calculated diffusion coefficients. The same steps were followed for both groups.

1.1 Statistical Analysis - Theory

The following sub-sections describe the theory of the statistics used in the analysis. The results of the statistical analysis are given in Section 1.2.

1.1.1 Statistical Descriptive Measures (μ, σ, V)

The first step in the data analysis was the determination of the key statistical parameters for each data group. The mean (μ), standard deviation (σ) and the coefficient of variation (V) were calculated for each group. The mean is the average chloride level (or diffusion coefficient) in the data group and is calculated using the equation $\mu = \frac{\sum_{i=1}^{n} x_i}{n}$, where $\mathbf{x_i}$ is the individual data point and **n** is the total number of data points. The standard deviation provides a measure of the central tendency of the data set about the mean. It is determined using the equation $\sigma = \sqrt{\frac{\sum_{i=1}^{n} (x_i - \mu)^2}{n-1}}$, where $\mathbf{x_i}$, **n** and **μ** are as described above. A larger standard deviation indicates high scatter of the data from the mean while a smaller standard deviation indicates a tighter data set about the mean. The coefficient of variation is a measure of the relative variation of the data about the mean and is given by the following formula, $V = \frac{\sigma}{\mu}$. The coefficient of variation provides the standard deviation as a percentage the mean. This allows the standard deviations of several data sets to be compared on an equivalent scale. A lower coefficient of variation indicates a more accurate data set, that is, less scatter in the data. This relationship is useful in determining the effect of a transformation on the data set by comparing **V**

before and after the transformation. Transformations on the data groups will be discussed in Section 1.1.3.

1.1.2 Normality of the Data Groups

The tests used to make a statistical comparison of the chloride levels and diffusion coefficients in the magnesium chloride deiced bridges and the sodium chloride deiced bridges have a requirement that the source data come from a normal population. That is, if an infinite number of samples were taken, the distribution of the data about the mean would take the shape of a normal probability curve, also know as the "bell curve". Two techniques were used in this study to assess the "normality" of the data groups, histograms and normal scores plots.

Histograms

Histograms were created to plot the frequency distribution of each data group. A histogram graphically illustrates the frequency distribution of the data. That is, the number of data points that fall between any given interval. Histograms give a quick indication of whether or not the data is normally distributed. The histogram will take the shape of a bell curve if the data is normally distributed. A typical histogram is given in Figure 2.

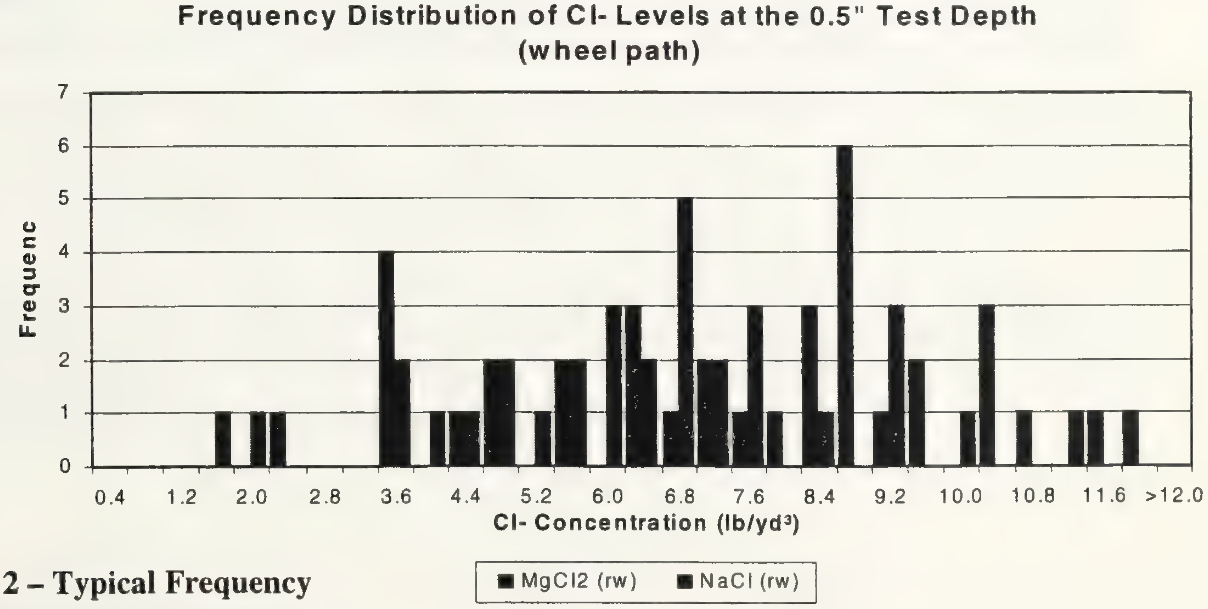

Figure 2 – Typical Frequency Distribution Plot (Histogram)

In Figure 2, the magnesium chloride (rw) series seems to be skewed to the right. That is, there are more values higher than the average than lower than the average. The sodium chloride (rw) series seems to be more "bell-shaped", but it is not extremely clear. In order to make a more accurate assessment of the normality of the data, a second, more rigorous method should be employed. Normal-scores plots provide a better indication of whether or not the data follows a normal distribution.

Normal-Scores Plots

The second method of testing normality is the normal-scores plot. A normal-scores plot is a plot of the observed data against the idealized normal distribution.[1] The observed data is sorted in increasing magnitude and a normal-score is calculated for each data point. The observed data is then plotted against its normal-score. A discussion of normal score values is required.

The normal-score is a value taken from the standard normal probability plot. It is also referred to as the z-score. The standard normal probability plot (or bell curve) is a bell curve with a mean of 0 and a standard deviation of 1. The variable **z** is the independent variable (on horizontal axis) on the bell curve plot. For each value of **z**, there is a corresponding probability of that value of **z** occurring in a series of observations, read off of the bell curve. **Z** can be calculated for any data point of a data set, provided the mean and standard deviation of the data set are known or have been calculated. **Z** is calculated using the formula $Z = \frac{x - \mu}{\sigma}$. Using this formula, a standardized value can be calculated for any data point, regardless of magnitude. Using the **z** values from the standard bell curve, the normal-score plot can be constructed.

The number of data points in question determines the **z** values used for the normal-scores plot. For example, if there are 4 observed data points, the standard bell curve is divided into 5 equal parts. This gives 4 **z** values (or normal scores) at equal intervals. This is illustrated on the normal probability plot shown in Figure 3.

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[1] Miller, Freund, Johnson; Probability and Statistics for Engineers; pages 171-173 for explanation of normal-scores

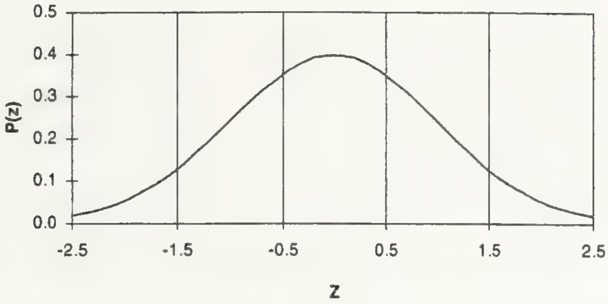

Figure 3 – Standard Normal Probability Plot

The observed data points are sorted in order of increasing magnitude. Each observed data point is given a corresponding z-score, depending on where it ranks. For example, the smallest data point would be given a z-score of –1.5, the second smallest point would be given a z-score of –0.5 and so on. A plot is then made of the normal-score versus the observed value, with the normal-score being on the x-axis. Data is considered to have a normal probability distribution if the plot of its normal-scores is linear in nature. The closer the data plots to a straight line, the more valid the assumption of a normal distribution is. An example of a normal-scores plot is given in Figure 4.

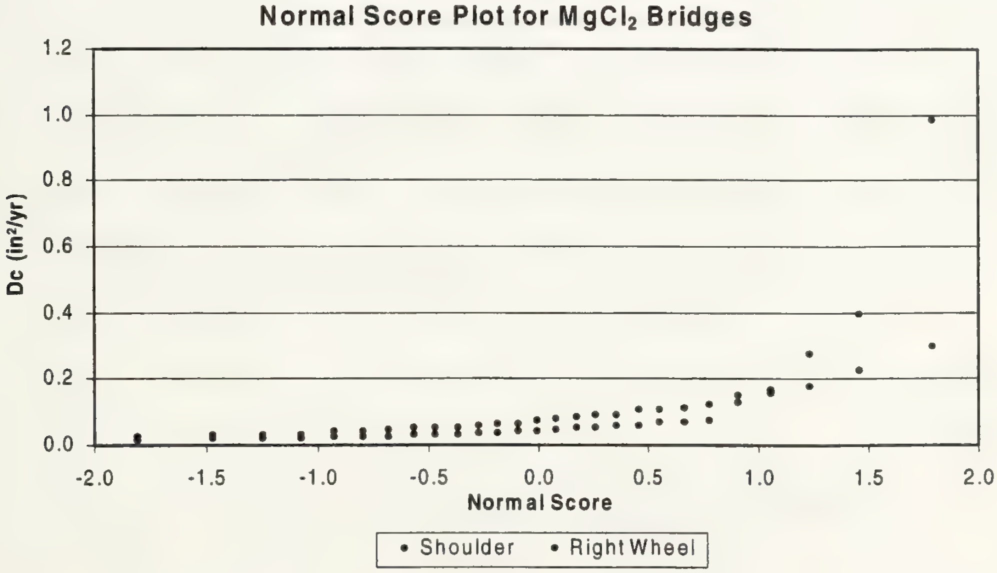

Figure 4 – Normal-Scores Plot of D_c Values

Notice that the normal-scores plot in Figure 4 is not linear. Its shape is similar to an exponential curve. This shape suggests that a mathematical transformation is needed to give the data set a normal distribution.

1.1.3 Transformation of the Data to a Normal Distribution

In order to approximate a normal population more accurately, a data set can be subjected to several types of mathematical transformations. The type of transformation used generally depends on the manner in which the data plots on the normal-scores plot. In the case of the data plotted in Figure 4, an exponential pattern in the data is observed. In order to create a linear relationship, the larger data points must be decreased in magnitude while the smaller values remain relatively unchanged. Several mathematical relationships can be used to achieve this transformation, among them ln (x), $x^{1/2}$ and $x^{1/4}$, where **x** is the original value of the data. It should be noted that these transformations are applied only for statistical purposes. They are not used to make the data correlate better. The transformed values are only used during statistical tests and following the tests, are converted back to their original value by reversing the transformation.

In order to determine which transformation relationship is best for the data, the data is subjected to each transformation. Following the transformation of the data by the relationships mentioned previously, a regression analysis is performed to determine which transformation provided the most linear normal-scores plot.

The first step of the regression analysis involves the creation of best-fit lines for the original data and the transformed data against the normal-scores data. The closer the data is to the best-fit line on the normal-scores plot, the better the data fits a normal probability distribution. The residual value defines this "closeness". The residual is the numerical difference between the y-value of the actual data point and the y-value of the best-fit line at the same location on the x-axis as the actual data point. Residuals are illustrated in Figure 5 below.

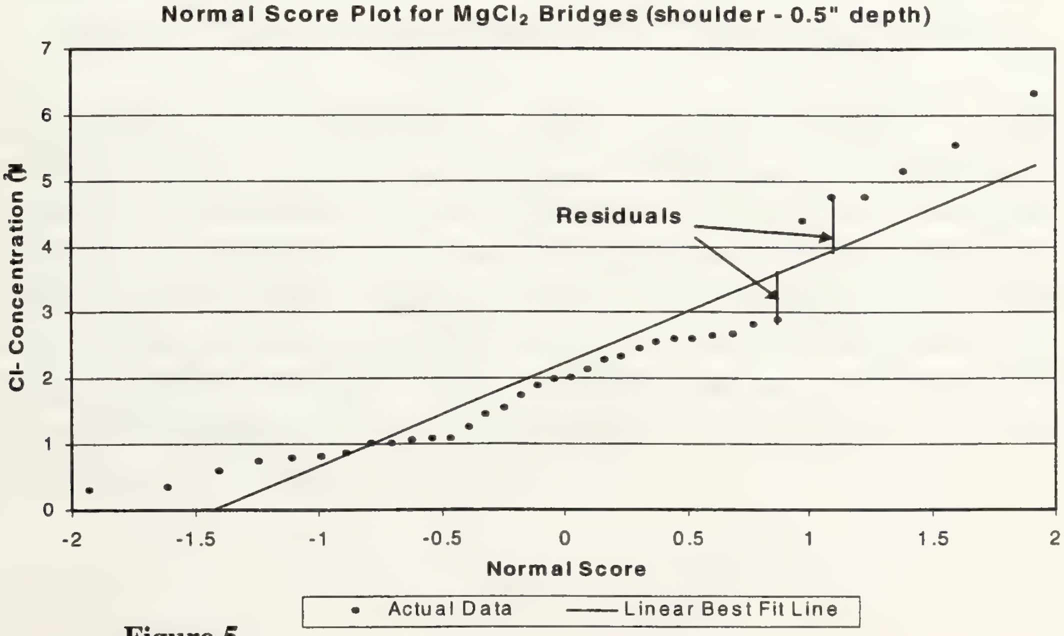

Figure 5

Figure 5 shows a linear best-fit line created for the normal-scores plot of chlorides at the 0.5in. (12.5mm) depth along the shoulder line of magnesium chloride exposed bridges. If the observed data or the transformed data is relatively close to the best-fit line on the normal-scores plot, it indicates a near-normal distribution. The plot of the residuals for each data series (original data and transformed data) against the normal-scores provides a strong indication of which transformation, if any, makes the data fit the normal distribution in the most accurate manner. Figure 6 shows a typical residual plot used in this study.

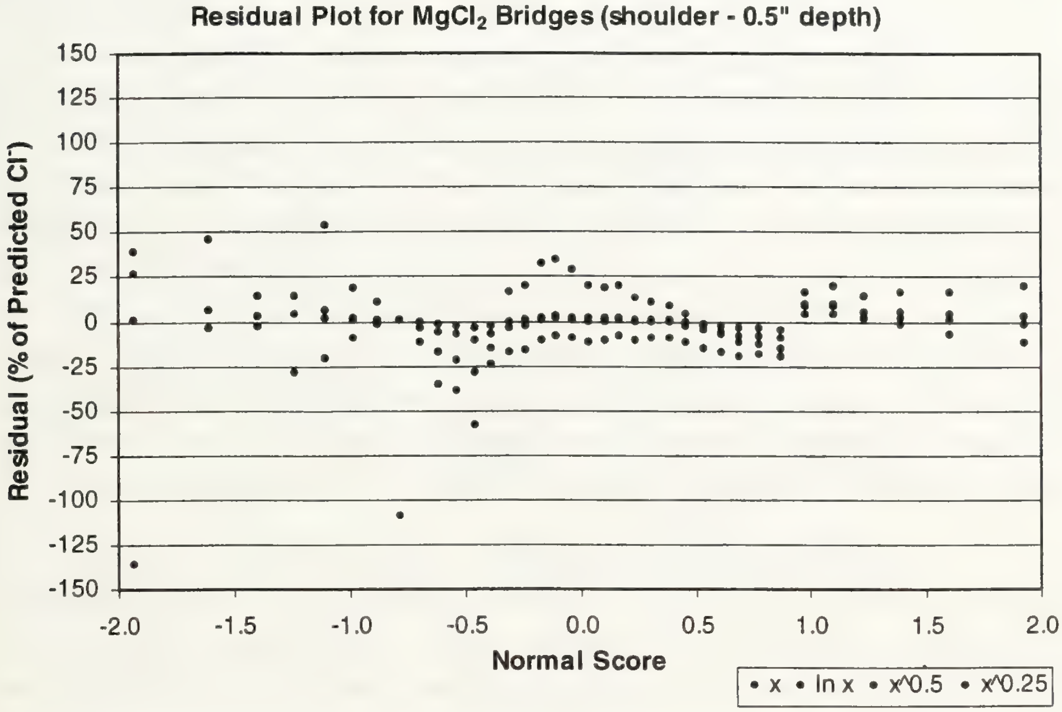

Figure 6 – Normal-Scores Residual Plot for Transformed Chlorides

The residuals have been plotted as a percentage of the predicted value. By doing this, all the residuals are on an equal scale and can be compared visually. In Figure 6, each series represents a different data transformation. The series with residual values closest to 0%, on average, gives the transformation that best approximates a normal distribution.

Now that the data has been transformed so that it fits the normal probability distribution, statistical tests, such as hypothesis tests, can be performed on the data set(s). Hypothesis testing was used in this study to determine the differences between bridge decks exposed to magnesium chloride deicer and decks exposed to sodium chloride deicer. Hypothesis testing is explained in the following section.

1.1.4 Hypothesis Testing

The hypothesis testing completed in this study can be grouped into three tests/calculations. The z-test (or t-test) is performed to compare averages of two data sets. The F-test is performed to compare the standard deviations of two data sets. Finally, a confidence interval calculation is made to determine the range of difference between two data, given a certain level of allowable error. These three groups are described, in detail, in the remainder of Section 1.1.4.

The z and t-Tests

The primary statistical test for comparing two sample groups is the hypothesis test. In this test, a hypothesis is chosen, called the null hypothesis, and a statistical test is performed to determine if the data satisfies the hypothesis. In the case of this study, comparisons between the chloride levels on magnesium chloride and sodium chloride treated bridges and diffusion coefficients of magnesium chloride and sodium chloride treated bridges were required. The null hypothesis that was chosen for this study was that the average chloride level/diffusion coefficient of the magnesium chloride decks (μ_{Mg}) at a specific depth and location was equal to the average chloride level/diffusion coefficient in the sodium chloride decks (μ_{Na}) at the same depth and location. A second hypothesis, the alternate hypothesis, is made for the cases where the null hypothesis does not pass the test. The alternate hypothesis chosen for this study was that μ_{Mg} was greater than μ_{Na}.

The z-test was used in this study to determine whether or not there was a statistical difference between the chloride levels/diffusion coefficients on magnesium chloride and sodium chloride treated bridges. In the z-test, a value **z** is calculated from the means and standard deviations of the data sets being compared.[2] **Z** is computed using the following formula: $z = \dfrac{\mu_1 - \mu_2 - \delta}{\sqrt{\dfrac{\sigma_1^2}{n_1} + \dfrac{\sigma_2^2}{n_2}}}$, where μ, σ and n are the mean, standard deviation and number of data points, respectively, and δ is the hypothesis constant. Since we are dealing with a null hypothesis (i.e. $\mu_1 - \mu_2 = 0$), $\delta = 0$. The calculated value of **z** is then compared to a value of **z** read from the normal probability plot, as discussed in Section 1.1.2. If the computed value of **z** lies between **z** and **–z** read from the normal probability curve, the null hypothesis is correct. Otherwise, the null hypothesis is not true and the alternate hypothesis must be accepted.

The **z** value that is taken from the normal probability plot is determined by the "level of significance" that is chosen for the test. For this study, a level of significance of 5% was

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[2] Miller, Freund, Johnson; Probability and Statistics for Engineers; pages 240-242 for explanation of z-test

deemed sufficient. That is, there is only a 5% chance that the result from the z-test would be an error. The level of significance is referred to as α in the hypothesis test. Since the "bell curve" is symmetrical about the mean, the level of significance must be divided by two in order to account for cases where the difference in the means is a positive or a negative number. That is, the chance of error is ± 2.5%, for a total chance of error of 5%.

In cases where smaller sample sizes exist (the number of samples is less than 30), another test, similar to the z-test, should be used for greater accuracy. This test, called the t-test, is also a hypothesis test. The difference in the t-test is the variable that is compared. In the t-test, a variable **t** is calculated and then compared to a value of **t** for a certain level of significance. The t-variable is much like the z-variable, except that it accounts for the size of the sample in its calculation. It is calculated according using the following formula: $t = \frac{\overline{x_1} - \overline{x_2} - \delta}{\sqrt{(n_1 - 1)s_1^2 + (n_2 - 1)s_2^2}} \sqrt{\frac{n_1 n_2 (n_1 + n_2 - 2)}{n_1 + n_2}}$, where $\overline{x}$, **s** and **n** are the mean, standard deviation and number of data points, respectively, and δ is the hypothesis constant mentioned previously. In the calculation of **t**, $\overline{x}$ and **s** replace μ and σ because it is assumed that due to the small number of data points, the data set is a sample rather than an accurate representation of the population. The value of t that is compared to the value calculated using the formula above is taken from a t-distribution. The t-distribution is much like the normal distribution. However, depending on the size of the data set, the shape of the t-distribution changes. The shape is defined by the degree of freedom of the data set. The degree of freedom is calculated using the formula $\nu = n - 1$, where n is the number of data points in the set. When the degree of freedom approaches 30, the t-distribution approximates the normal distribution used in the z-test. The normal distribution is actually a specific case of the t-distribution when the degree of freedom approaches infinity (or for practical purposes, greater than 30). Because the sample sizes in this study were typically less than 30, the t-test was used instead of the z-test.

The F-test

A second test performed on the magnesium chloride and sodium chloride data sets was the F-test. This test compares the variances (square of the standard deviations) of the two data sets instead of the means, which were compared in the t-test.[3] The steps taken in this test are the same as in the t-test, except that a different probability plot is used. Instead of the normal probability plot, the F-distribution is used. This distribution provides a statistic based on the ratio of the sizes of the two data sets and the probability of error (the same probability of error used for the z-test was used for the F-test). The result of the F-test, like the t-test, is the acceptance or rejection of a null hypothesis. The null hypothesis

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[3] Miller, Freund, Johnson; Probability and Statistics for Engineers; pages 263-264 for explanation of F-test

used in this study was $\sigma_{Mg}^2 = \sigma_{Na}^2$. If the calculated value of **F** is greater than the value of **F** from the F-distribution, the null hypothesis must be rejected and the alternate hypothesis of $\sigma_{Mg}^2 > \sigma_{Na}^2$ is true.

In addition to comparing the variances of two data sets, the F-test verifies or discredits an assumption made for the z and t-tests. In the z and t-tests, where the means of two data sets are compared for equality, it was assumed that the variances of the two data sets were statistically equal. The F-test verifies if that assumption was valid. In cases where the F-test shows the variances to be unequal, one must be cautious about applying the results of the t-test, since the underlying assumption of the test is not completely accurate.

Confidence Intervals

In cases where a difference in the means is identified, the likely size of that difference can be determined using a confidence interval calculation. Confidence intervals are calculated because there is uncertainty in the numerical difference ($\mu_1 - \mu_2$) of the means. Each of the data sets has some variation in it. This is quantified by the data set's standard deviation. Since each data set has a certain variation from its mean value, the difference between the mean values of the data sets will also have some variation. It is this variation in the difference that is determined by performing a confidence interval calculation.

The confidence interval provides a range of likely values of $\mu_1 - \mu_2$. The interval is calculated as $\mu_1 - \mu_2 \pm z\sigma$. In this case, **z** is calculated based on the level of significance that is chosen. For a level of significance of ± 2.5%, as used in the previous tests, $z = 1.96$. If the t-test is used, as in this study, the confidence interval is calculated in the same manner, replacing **z** with **t** in the formula above. The result of the confidence interval calculation is a range in the difference for a given probability.

1.2 Statistical Analysis - Results

1.2.1 Statistical Descriptive Measures (μ, σ, V)

Chloride Data

The descriptive measures calculated for each chloride data group are shown in Appendix A-6. For the magnesium chloride treated bridges, the coefficients of variation range from 0.34 to 1.55. **V** ranges from 0.34 to 1.89 for the sodium chloride treated bridges and from 0.50 to 1.36 for the rehabilitated bridges. These values of **V** give the first indication that the data set is fairly scattered and that the data may need to be transformed in order to do a statistical comparison between the magnesium chloride bridges and the sodium chloride bridges.

Diffusion Coefficients

The descriptive measures described in Section 1.1.1 and calculated for the chloride data were calculated for the D_c values. Appendix A-7 shows these measures, sorted by bridge type and test line location. In the case of the D_c values along the shoulder line, for both magnesium chloride and sodium chloride bridges, V ranges from 1.42 to 1.93. This indicates a very high degree of scatter in the data and like the chloride data, gives a strong indication that a transformation may be required. The D_c values calculated for the right wheel line show less scatter, with V ranging from 0.55 to 0.80.

1.2.2 Normality of the Data Groups

Chloride Data

- Histograms

Histograms for the three bridge types are provided in Appendix A-8. A histogram was created for each test depth (0.5in. (12.5mm), 1.5in. (37.5mm) and 2.25in. (56.3mm)) and each test location (shoulder and wheel path), with the frequency distribution of the readings from the magnesium chloride bridges and sodium chloride bridges being compared on the plot. The histogram plots indicated that the data was somewhat normal in distribution, but that deviation from the normal distribution did exist (shown by long tail sections and a lack of symmetry). Due to this uncertainty a second method of testing normality of the data was performed.

- Normal-Scores Plots

The normal-scores plots for the three bridge types are provided in Appendix A-9. A normal-scores plot was generated for each bridge type (magnesium chloride, sodium chloride, rehabilitated) and for each line of testing (shoulder, right wheel line). Each test depth is shown on the normal-scores plot. The normal-scores plots show that the data has a tendency to deviate more from a straight line as the normal-score increases. This trend provides sufficient evidence that the data should be transformed prior to statistical analysis in order to give the most accurate results.

Diffusion Coefficients

- Histograms

Histogram plots for the shoulder and right wheel D_c values for the two bridge types are included in Appendix A-10. It should be noted that the average D_c for each test hole was used in the statistical analysis, including histograms, normal-scores plots and regression calculations. The histograms show the same type of skewness in the distribution as the chloride data showed. In addition, there is a greater frequency of D_c values greater than the average D_c of each group (i.e. skewed to the right).

- Normal-Scores Plots

Normal-scores plots were created for the magnesium chloride and sodium chloride bridges and are given in Appendix A-11. These plots use the average D_c value calculated at each test hole as their data source. The normal-scores plots show a clear trend in the D_c data. In all four groups, an exponential-type pattern in the normal-scores data is visible. As was the case with the chloride data, a transformation such as ln (D_c), $D_c^{1/2}$ or $D_c^{1/4}$ seems appropriate in order to achieve a normal distribution of the D_c values.

1.2.3 Transformation of the Data to a Normal Distribution

Chloride Data

Residual plots for all the test depths and test locations on the magnesium chloride bridges are given in Appendix A-12. Since the normal-scores plots for the sodium chloride bridges were similar in shape as the plots for the magnesium chloride bridges, residuals were only calculated for the magnesium chloride bridges. The residual plots show that the data transformed by the expression $y = x^{1/4}$ are closest to 0% in the majority of the cases. Thus, $y = x^{1/4}$ is the most accurate transformation to use to make the data fit the normal probability distribution. The transformed data for the three bridge types is given in Appendix A-13.

For comparison purposes, the descriptive measures discussed in Section 1.1.1 were recalculated for the $X^{1/4}$-transformed data. The descriptive measures are given in Appendix A-14. The effect of the transformation of the data is clear when values of **V** are examined. For example, for magnesium chloride bridges, values of **V** along the right wheel line for the original data were 0.69, 0.88 and 1.55 for the 0.5in. (12.5mm), 1.5in. (37.5mm) and 2.25in. (56.3mm) depths. Values of **V** for the same locations for the transformed data were 0.18, 0.35 and 0.61. This significant reduction in **V** indicates that the transformed data is much tighter about the mean and more normal in distribution.

Diffusion Coefficients

The three transformations described in Section 1.1.3 were applied to the calculated D_c values for the magnesium chloride and sodium chloride bridges. The same type of regression analysis used for the chloride data was used for the D_c values. Residual plots for the original and transformed values were generated for each bridge type and test line. The normal-scores residual plots for the diffusion coefficients are given in Appendix A-15. The residuals for the original calculated D_c values vary greatly, while the D_c values transformed by ln (D_c) or $D_c^{1/4}$ seem to be the closest to 0. When all the residual plots in Appendix A-15 are compared, the transformation of ln (D_c) appears to give the normal-

scores plot closest to a straight line and thus the best approximation of a normal distribution.

Appendix A-16 gives the ln-transformed average D_c values for each bridge type and test line. The descriptive measures calculated for the original D_c values were recalculated for the ln-transformed D_c values. These measures are given in Appendix A-7. When the descriptive measures of the ln-transformed values are examined, a drastic improvement in the data distribution is observed. Coefficients of variation that ranged from 0.55 to 1.93 for the original D_c data now range from 0.16 to 0.36 for the transformed D_c values. The transformed data is much less scattered than the original data and thus better approximates a normal distribution.

1.2.4 Hypothesis Testing

Chloride Data

The results of the hypothesis tests (t-test and F-test) and the confidence interval calculation performed for the chloride data are presented in Appendix A-17. A brief discussion of the results is provided below:

- *t-test Results*

Of the t-tests performed for the six groups (0.5in. (12.5mm), 1.5in. (37.5mm) and 2.25in. (56.3mm) shoulder and right wheel path) the null hypothesis was determined to be true for four of the groups. That is, the difference between the chloride levels in the magnesium chloride and sodium chloride bridges was not statistically significant in four of the six tests. The two groups that did produce statistically different chloride levels were the 1.5in. (37.5mm) and 2.25in. (56.3mm) depths along the right wheel line.

- *F-test Results*

The F-tests conducted showed that in all cases, with the exception of the 0.5in. (12.5mm) depth shoulder line group, the null hypothesis was true (i.e. the variances of the two groups were the same). The results from the F-test show that for the majority of the cases the assumptions used in the t-test were valid. In the case of the 0.5in. (12.5mm) depth along the shoulder line, the results of the t-test must be approached with some caution because of the negative result of the F-test.

- *Confidence Interval Calculations*

For the two groups that proved to have statistical differences according to the t-test, confidence interval calculations were performed to give probability ranges for the differences. At the 95% confidence level, the chloride levels at the 1.5in. (37.5mm) wheel line depth were found to be between 0.56 (0.33) and 2.28 lb/yd^3 (1.35 kg/m^3) higher in the magnesium chloride bridges than the sodium chloride bridges. At the

2.25in. (56.3mm) wheel line depth, the chloride levels in the magnesium chloride bridges were 0.16 (0.09) to 1.06 lb/yd^3 (0.63 kg/m^3) higher than the sodium chloride bridges.

Diffusion Coefficients

The same hypothesis tests (t-test and F-test) and confidence interval calculations given in Section 7.2.3.4 were applied to the D_c values in order to determine if there was a statistical difference in the diffusion coefficients of magnesium chloride and sodium chloride bridges. Two test groups now existed, one group comparing D_c values along the shoulder line of the two bridge types and the second comparing D_c along the right wheel path of the two bridge types. The results of the hypothesis tests (t-test and F-test) and the confidence interval calculation performed for the diffusion coefficients are given in Appendix A-18. A brief discussion of the results is provided below:

- t-test Results

The t-test showed that there was not a statistical difference between the average D_c for magnesium chloride bridges and sodium chloride bridges along the shoulder. However, a significant difference in average D_c did exist along the wheel line. Along the wheel line, D_c was found to be on average 0.048 in^2/yr (0.31 cm^2/yr) higher on magnesium chloride bridges than on sodium chloride bridges.

This result explains why there was a statistically significant difference in the chloride levels of the two bridge types at deeper depths, while there was not a significant difference at the upper depths. If a similar surface chloride level existed on both types of bridges, but diffusion coefficients were different, the bridge type with the higher diffusion coefficient would have higher chloride levels at lower depths. This was the case with the bridges exposed to magnesium chloride deicer.

- F-test Results

The F-tests done for the shoulder and wheel path groups show that the variances of the magnesium chloride and sodium chloride bridges are statistically equal. This means that the underlying assumption of the t-test is valid and therefore the t-test results are valid.

- Confidence Interval Calculations

The difference between average D_c values for magnesium chloride and sodium chloride bridges was found to range from 0.024 (0.15) to 0.072 in^2/yr (0.46 cm^2/yr) at a confidence level of 95%. With an average D_c of 0.040 in^2/yr (0.28 cm^2/yr) for sodium chloride bridges along the wheel line, this difference represents a 60% to 180% increase in D_c in magnesium chloride bridges!

Chloride Test Data for NaCl Treated Bridges

Bridge No.	Shoulder Line			Right Wheel Line		
	Sample Number	Sample Depth (in)	Uncorrected Cl^- (%)	Sample Number	Sample Depth (in)	Uncorrected Cl^- (%)
58 + 05502	1	0.5	0.044	2	0.5	0.048
	3	0.5	0.058	5	0.5	0.110
	4	0.5	0.077	7	0.5	0.056
	6	0.5	0.038	8	0.5	0.130
	3	1.5	0.014	2	1.5	0.009
	4	1.5	0.036	5	1.5	0.022
	6	1.5	0.010	7	1.5	0.007
	3	2.3	0.010	2	2.3	0.008
	6	2.3	0.007	5	2.3	0.010
	6	4.0	0.007	7	2.3	0.007
58 + 05501	1	0.5	0.016	5	0.5	0.180
	2	0.5	0.057	6	0.5	0.160
	3	0.5	0.057	7	0.5	0.220
	4	0.5	0.039	8	0.5	0.240
	2	1.5	0.021	5	1.5	0.060
	3	1.5	0.019	6	1.5	0.035
	4	1.5	0.020	7	1.5	0.086
	2	2.3	0.009	5	2.3	0.009
	3	2.3	0.023	6	2.3	0.013
				7	2.3	0.011
				6	4.0	0.007
42 + 09191	1	0.5	0.041	5	0.5	0.150
	2	0.5	0.055	6	0.5	0.170
	3	0.5	0.096	7	0.5	0.240
	4	0.5	0.050	8	0.5	0.200
	2	1.5	0.018	5	1.5	0.054
	3	1.5	0.007	6	1.5	0.035
	4	1.5	0.025	7	1.5	0.098
	2	2.3	0.008	5	2.3	0.009
	3	2.3	0.006	6	2.3	0.009
				7	2.3	0.012
				6	4.0	0.011
39 + 09912	1	0.5	0.078	5	0.5	0.180
	2	0.5	0.079	6	0.5	0.150
	3	0.5	0.071	7	0.5	0.094
	4	0.5	0.042	8	0.5	0.180
	2	1.5	0.012	5	1.5	0.020
	3	1.5	0.017	6	1.5	0.042
	4	1.5	0.009	7	1.5	0.029
	2	2.3	0.007	6	2.3	0.007
	3	2.3	0.009	7	2.3	0.009
				6	4.0	0.007

Chloride Test Data for NaCl Treated Bridges (cont'd)

Bridge No.	Shoulder Line			Right Wheel Line		
	Sample Number	Sample Depth (in)	Uncorrected Cl^- (%)	Sample Number	Sample Depth (in)	Uncorrected Cl^- (%)
39 + 09911	1	0.5	0.056	5	0.5	0.200
	2	0.5	0.074	6	0.5	0.260
	3	0.5	0.055	7	0.5	0.290
	4	0.5	0.050	8	0.5	0.190
	2	1.5	0.056	5	1.5	0.100
	3	1.5	0.040	6	1.5	0.087
	4	1.5	0.027	7	1.5	0.100
	2	2.3	0.052	5	2.3	0.046
	3	2.3	0.017	6	2.3	0.056
				7	2.3	0.053
				6	4.0	0.015
39 + 08052	1	0.5	0.100	5	0.5	0.190
	2	0.5	0.067	6	0.5	0.100
	3	0.5	0.093	7	0.5	0.180
	4	0.5	0.080	8	0.5	0.120
	2	1.5	0.025	5	1.5	0.080
	3	1.5	0.024	6	1.5	0.015
	4	1.5	0.022	7	1.5	0.100
	2	2.3	0.009	5	2.3	0.009
	3	2.3	0.007	6	2.3	0.009
				7	2.3	0.021
				6	4.0	0.008
34 + 02082	1	0.5	0.021	5	0.5	0.160
	2	0.5	0.054	6	0.5	0.240
	3	0.5	0.036	7	0.5	0.200
	4	0.5	0.036	8	0.5	0.160
	2	1.5	0.009	5	1.5	0.048
	3	1.5	0.021	6	1.5	0.083
	4	1.5	0.024	7	1.5	0.059
	2	2.3	0.007	5	2.3	0.013
	3	2.3	0.008	6	2.3	0.009
				7	2.3	0.009
				6	4.0	0.007
34 + 02081	1	0.5	0.051	5	0.5	0.170
	2	0.5	0.039	6	0.5	0.180
	3	0.5	0.020	7	0.5	0.140
	4	0.5	0.043	8	0.5	0.130
	2	1.5	0.031	5	1.5	0.062
	3	1.5	0.007	6	1.5	0.035
	4	1.5	0.018	7	1.5	0.031
	2	2.3	0.025	5	2.3	0.021
	3	2.3	0.007	6	2.3	0.009
				7	2.3	0.008
				6	4.0	0.009

Chloride Test Data for $MgCl_2$ Treated Bridges

PROJECT NUMBER: 77054-00-3

Bridge No.	Shoulder Line			Right Wheel Line		
	Sample Number	Sample Depth (in)	Uncorrected Cl^- (%)	Sample Number	Sample Depth (in)	Uncorrected Cl^- (%)
01+ 09821	1	0.5	0.029	5	0.5	0.230
	2	0.5	0.130	6	0.5	0.220
	3	0.5	0.140	7	0.5	0.270
	4	0.5	0.039	8	0.5	0.210
	2	1.5	0.046	5	1.5	0.120
	3	1.5	0.044	6	1.5	0.140
	4	1.5	0.010	7	1.5	0.130
	2	2.3	0.015	5	2.3	0.052
	3	2.3	0.010	6	2.3	0.048
				7	2.3	0.029
				6	4.0	0.015
05 + 01481	1	0.5	0.170	5	0.5	0.220
	2	0.5	0.150	6	0.5	0.230
	3	0.5	0.130	7	0.5	0.180
	4	0.5	0.120	8	0.5	0.310
	2	1.5	0.027	5	1.5	0.061
	3	1.5	0.033	6	1.5	0.100
	4	1.5	0.049	7	1.5	0.110
	2	2.3	0.012	5	2.3	0.008
	3	2.3	0.011	6	2.3	0.010
				7	2.3	0.020
				6	4.0	0.011
06 + 05481	1	0.5	0.065	5	0.5	0.130
	2	0.5	0.047	6	0.5	0.100
	3	0.5	0.027	7	0.5	0.099
	4	0.5	0.075	8	0.5	0.090
	2	1.5	0.012	5	1.5	0.060
	3	1.5	0.008	6	1.5	0.033
	4	1.5	0.028	7	1.5	0.041
	2	2.3	0.016	5	2.3	0.034
	3	2.3	0.008	6	2.3	0.013
				7	2.3	0.009
				6	4.0	0.009
10 + 01221	1	0.5	0.014	5	0.5	0.150
	2	0.5	0.016	6	0.5	0.150
	3	0.5	0.022	7	0.5	0.130
	4	0.5	0.035	8	0.5	0.059
	2	1.5	0.009	5	1.5	0.061
	3	1.5	0.010	6	1.5	***0.055***
	4	1.5	0.017	7	1.5	0.044
	2	2.3	0.006	5	2.3	0.009
	3	2.3	0.007	6	2.3	***0.008***
				7	2.3	0.009
				6	4.0	0.009
10 + 07441	1	0.5	0.059	5	0.5	0.120
	2	0.5	0.070	6	0.5	0.230
	3	0.5	0.076	7	0.5	0.095
	4	0.5	0.062	8	0.5	0.170
	2	1.5	0.027	5	1.5	0.027
	3	1.5	0.031	6	1.5	0.028
	4	1.5	0.011	7	1.5	0.013
	2	2.3	0.009	5	2.3	0.008
	3	2.3	0.011	6	2.3	0.012
				7	2.3	0.014
				6	4.0	0.008

Chloride Test Data for $MgCl_2$ Treated Bridges (cont'd)

Bridge No.	Shoulder Line			Right Wheel Line		
	Sample Number	Sample Depth (in)	Uncorrected Cl$^-$ (%)	Sample Number	Sample Depth (in)	Uncorrected Cl$^-$ (%)
23 + 00631	1	0.5	0.052	5	0.5	0.250
	2	0.5	0.026	6	0.5	0.190
	3	0.5	0.028	7	0.5	0.270
	4	0.5	0.033	8	0.5	0.230
	2	1.5	0.008	5	1.5	0.100
	3	1.5	0.007	6	1.5	0.078
	4	1.5	0.008	7	1.5	0.078
	2	2.3	0.007	5	2.3	0.035
	3	2.3	0.006	6	2.3	0.010
				7	2.3	0.020
				6	4.0	0.015
29 + 02051	1	0.5	0.076	5	0.5	0.230
	2	0.5	0.074	6	0.5	0.280
	3	0.5	0.073	7	0.5	0.300
	4	0.5	0.059	8	0.5	0.270
	2	1.5	0.034	5	1.5	0.120
	3	1.5	0.049	6	1.5	0.190
	4	1.5	0.049	7	1.5	0.180
	2	2.3	0.015	5	2.3	0.060
	3	2.3	0.048	6	2.3	0.100
				7	2.3	0.080
				6	4.0	0.018
29 + 02052	1	0.5	0.035	5	0.5	0.170
	2	0.5	0.033	6	0.5	0.190
	3	0.5	0.034	7	0.5	0.170
	4	0.5	0.044	8	0.5	0.200
	2	1.5	0.023	5	1.5	0.130
	3	1.5	0.021	6	1.5	0.078
	4	1.5	0.031	7	1.5	0.096
	2	2.3	0.014	5	2.3	0.063
	3	2.3	0.015	6	2.3	0.023
				7	2.3	0.025
				6	4.0	0.014
29 + 03682	1	0.5	0.083	5	0.5	0.240
	2	0.5	0.074	6	0.5	0.220
	3	0.5	0.056	7	0.5	0.250
	4	0.5	0.067	8	0.5	0.230
	2	1.5	0.012	5	1.5	0.120
	3	1.5	0.017	6	1.5	0.110
	4	1.5	0.013	7	1.5	0.160
	2	2.3	0.011	5	2.3	0.039
	3	2.3	0.010	6	2.3	0.035
				7	2.3	0.075
				6	4.0	0.009

Chloride Test Data for Rehabilitated Bridges

Bridge No.	Shoulder Line			Right Wheel Line		
	Sample Number	Sample Depth (in)	Uncorrected Cl^- (%)	Sample Number	Sample Depth (in)	Uncorrected Cl^- (%)
57 + 04722	1	0.5	0.100	5	0.5	0.180
(epoxy)	2	0.5	0.032	6	0.5	0.058
	3	0.5	0.080	7	0.5	0.170
	4	0.5	0.093	8	0.5	0.110
	2	1.5	0.014	5	1.5	0.110
	3	1.5	0.027	6	1.5	0.042
	4	1.5	0.059	7	1.5	0.150
	2	2.3	0.007	5	2.3	0.037
	3	2.3	0.018	6	2.3	0.024
				7	2.3	0.086
				6	4.0	0.011
53 + 07232	1	0.5	0.052	5	0.5	0.140
(latex)	2	0.5	0.044	6	0.5	0.098
	3	0.5	0.095	7	0.5	0.077
	4	0.5	0.050	8	0.5	0.110
	2	1.5	0.008	5	1.5	0.042
	3	1.5	0.011	6	1.5	0.023
	4	1.5	0.006	7	1.5	0.010
	2	2.3	0.033	5	2.3	0.077
	3	2.3	0.022	6	2.3	0.057
				7	2.3	0.037
				6	4.0	0.010
45 + 01802	1	0.5	0.024	5	0.5	0.038
(epoxy)	2	0.5	0.019	6	0.5	0.083
	3	0.5	0.033	7	0.5	0.032
	4	0.5	0.043	8	0.5	0.130
	2	1.5	0.007	5	1.5	0.007
	3	1.5	0.013	6	1.5	0.025
	4	1.5	0.029	7	1.5	0.006
	2	2.3	0.007	5	2.3	0.006
	3	2.3	0.005	6	2.3	0.007
				7	2.3	0.007
				6	4.0	0.005

Background Cl^- Calculation for $MgCl_2$ Treated Bridges

Bridge No.	Sample Depth (in)	Avg. Cl^- (lb/yd^3) at Each Depth	D_c (in^2/yr)	Diffused Cl^- @ 4.0" (lb/yd^3)	Background Cl^- (lb/yd^3)
01+ 09821	0.5	6.15	*0"-1.5" : 0.1294*		
	1.5	3.17	*0"-2.25" : 0.0728*		
	2.3	1.20			
	4.0	0.58	Average: 0.1011	0.31	0.27
05 + 01481	0.5	7.31	*0"-1.5" : 0.0582*		
	1.5	2.44	*0"-2.25" : 0.0359*		
	2.3	0.46			
	4.0	0.43	Average: 0.0471	0.03	0.40
06 + 05481	0.5	3.06	*0"-1.5" : 0.0704*		
	1.5	1.16	*0"-2.25" : 0.0759*		
	2.3	0.62			
	4.0	0.35	Average: 0.0732	0.06	0.28
10 + 01221	0.5	2.79	*0"-1.5" : 0.0988*		
	1.5	1.28	*0"-2.25" : 0.0477*		
	2.3	0.31			
	4.0	0.35	Average: 0.0733	0.06	0.29
10 + 07441	0.5	4.26	*0"-1.5" : 0.0346*		
	1.5	0.89	*0"-2.25" : 0.0451*		
	2.3	0.43			
	4.0	0.31	Average: 0.0398	0.01	0.30
23 + 00631	0.5	5.22	*0"-1.5" : 0.0617*		
	1.5	1.82	*0"-2.25" : 0.0505*		
	2.3	0.62			
	4.0	0.58	Average: 0.0561	0.05	0.54
29 + 02051	0.5	6.62	***Corrected Dc***		
	1.5	4.02			
	2.3	2.36			
	4.0	0.70	***Average: 0.1124***	*0.42*	*0.28*
29 + 02052	0.5	4.26	*0"-1.5" : 0.1647*		
	1.5	2.40	*0"-2.25" : 0.0940*		
	2.3	1.08			
	4.0	0.54	Average: 0.1293	0.35	0.19
29 + 03682	0.5	5.88	*0"-1.5" : 0.1024*		
	1.5	2.75	*0"-2.25" : 0.0827*		
	2.3	1.32			
	4.0	0.35	Average: 0.0925	0.11	0.24
Average Background Cl^- for $MgCl_2$ Bridges					**0.31**

Background Cl$^-$ Calculation for NaCl Treated Bridges

Bridge No.	Sample Depth (in)	Avg. Cl$^-$ (lb/yd^3) at Each Depth	D$_c$ (in^2/yr)	Diffused Cl$^-$ @ 4.0" (lb/yd^3)	Background Cl$^-$ (lb/yd^3)
34 + 02081	0.5	3.75	*0"-1.5" : 0.0547*		
	1.5	1.20	*0"-2.25" : 0.0574*		
	2.3	0.54			
	4.0	0.27	Average: 0.0561	0.03	0.24
34 + 02082	0.5	4.37	*0"-1.5" : 0.0654*		
	1.5	1.59	*0"-2.25" : 0.0403*		
	2.3	0.35			
	4.0	0.35	Average: 0.0529	0.03	0.32
39 + 08052	0.5	4.53	*0"-1.5" : 0.0727*		
	1.5	1.74	*0"-2.25" : 0.0435*		
	2.3	0.43			
	4.0	0.27	Average: 0.0581	0.04	0.23
39 + 09911	0.5	5.69	*0"-1.5" : 0.1005*		
	1.5	2.63	*0"-2.25" : 0.1180*		
	2.3	1.74			
	4.0	0.31	Average: 0.1093	0.33	-0.02
39 + 09912	0.5	4.22	*0"-1.5" : 0.0319*		
	1.5	0.81	*0"-2.25" : 0.0379*		
	2.3	0.31			
	4.0	0.58	Average: 0.0349	0.01	0.58
42 + 09191	0.5	4.84	*0"-1.5" : 0.0550*		
	1.5	1.55	*0"-2.25" : 0.0382*		
	2.3	0.35			
	4.0	0.27	Average: 0.0466	0.02	0.25
58 + 05501	0.5	4.68	*0"-1.5" : 0.0576*		
	1.5	1.55	*0"-2.25" : 0.0475*		
	2.3	0.50			
	4.0	0.43	Average: 0.0526	0.03	0.40
58 + 05502	0.5	2.71	*0"-1.5" : 0.0378*		
	1.5	0.62	*0"-2.25" : 0.0486*		
	2.3	0.31			
	4.0	0.27	Average: 0.0432	0.01	0.26
Average Background Cl$^-$ for NaCl Bridges					**0.28**

Background Cl^- Calculation for Rehabilitated Bridges

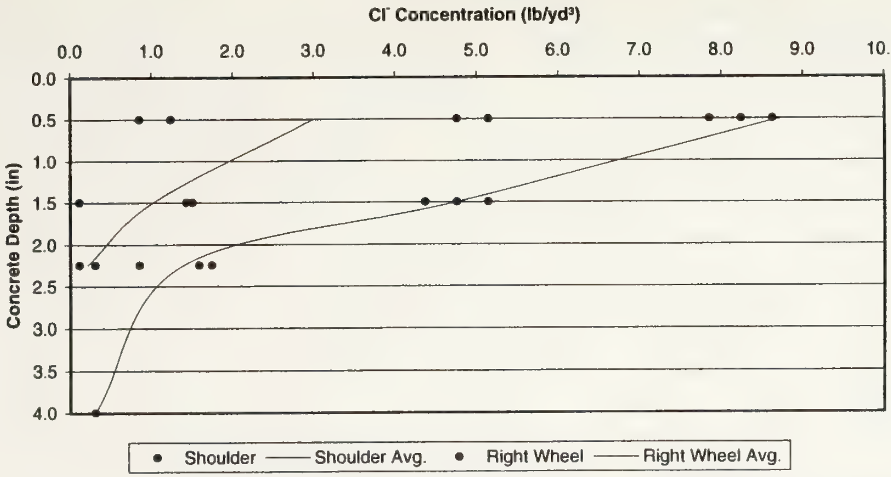
Bridge No.	Sample Depth (in)	Avg. Cl^- (lb/yd^3) at Each Depth	D_c (in^2/yr)	Diffused Cl^- @ 4.0" (lb/yd^3)	Background Cl^- (lb/yd^3)
45 + 01802	0.5	1.94	*0"-1.5" : 0.0516*		
	1.5	0.58	*0"-2.25" : 0.0513*		
	2.3	0.23			
	4.0	0.19	Average: 0.0515	0.01	0.18
53 + 07232	0.5	3.21	***Corrected Dc***		
	1.5	0.66			
	2.3	1.74			
	4.0	0.39	***Average: 0.0882***	*0.12*	*0.27*
57 + 04722	0.5	3.99	***Corrected Dc***		
	1.5	2.59			
	2.3	1.32			
	4.0	0.43	***Average: 0.0896***	*0.15*	*0.28*
Average Background Cl^- for Rehabilitated Bridges					**0.24**

Overall Average Background Cl^- Level (lb/yd^3)	**0.27**

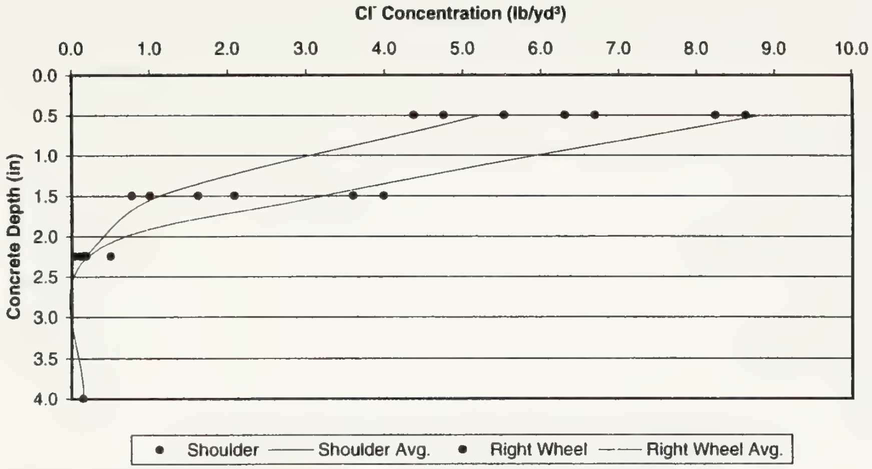
Chloride Data (corrected) for $MgCl_2$ Treated Bridges

Bridge No.	Cl^- Readings Along Shoulder (lb/yd^3)			Cl^- Readings Along Right Wheel (lb/yd^3)		
	0.5" Test Depth	1.5" Test Depth	2.25" Test Depth	0.5" Test Depth	1.5" Test Depth	2.25" Test Depth
01+ 09821	4.76	1.51	0.35	8.63	4.37	1.74
	0.85	1.43	0.12	10.37	4.76	0.85
	5.15	0.12		7.86	5.15	1.59
	1.24			8.24		
05 + 01481	5.53	0.77	0.19	8.24	1.99	0.04
	6.31	1.01	0.15	6.70	3.99	0.50
	4.76	1.63		11.73	3.60	0.12
	4.37			8.63		
06 + 05481	1.55	0.19	0.35	4.76	2.03	1.04
	2.28	0.04	0.04	3.56	1.32	0.08
	0.77	0.81		3.21	1.01	0.23
	2.63			3.60		
10 + 01221	0.35	0.08	0.00	5.53	2.11	0.08
	0.29	0.12	0.00	4.76	1.43	0.08
	0.58	0.39		2.01	1.86	0.04
	1.08			5.53		
10 + 07441	2.44	0.77	0.08	4.37	0.81	0.04
	1.97	0.93	0.15	3.41	0.23	0.27
	2.67	0.15		6.31	0.81	0.19
	2.13			8.63		
23 + 00631	0.74	0.04	0.00	9.40	3.60	1.08
	1.74	0.00	0.00	10.18	2.75	0.50
	0.81	0.04		8.63	2.75	0.12
	1.01			7.08		
29 + 02051	2.59	1.04	0.31	8.63	4.37	2.05
	2.81	1.63	1.59	11.34	6.70	2.83
	2.55	1.63		10.18	7.08	3.60
	2.01			10.57		
29 + 02052	1.01	0.62	0.27	6.31	4.57	2.17
	1.08	0.54	0.31	6.31	3.44	0.70
	1.04	0.93		7.47	2.75	0.62
	1.43			7.08		
29 + 03682	2.59	0.19	0.15	9.02	4.18	1.24
	2.88	0.39	0.12	9.40	5.92	2.63
	1.90	0.23		8.63	3.99	1.08
	2.32			8.24		

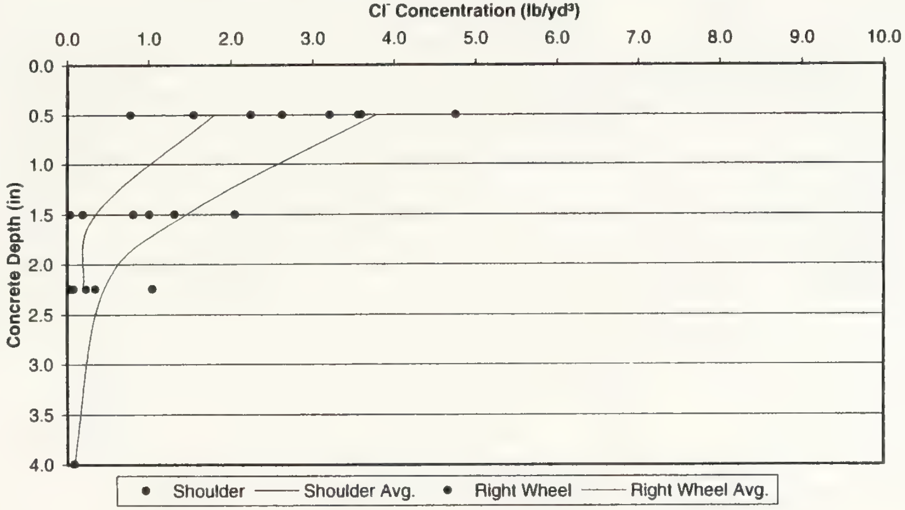
Chloride Concentration Profiles (corrected) for $MgCl_2$ Treated Bridges



Chloride Concentration vs. Depth for Bridge 01+09821

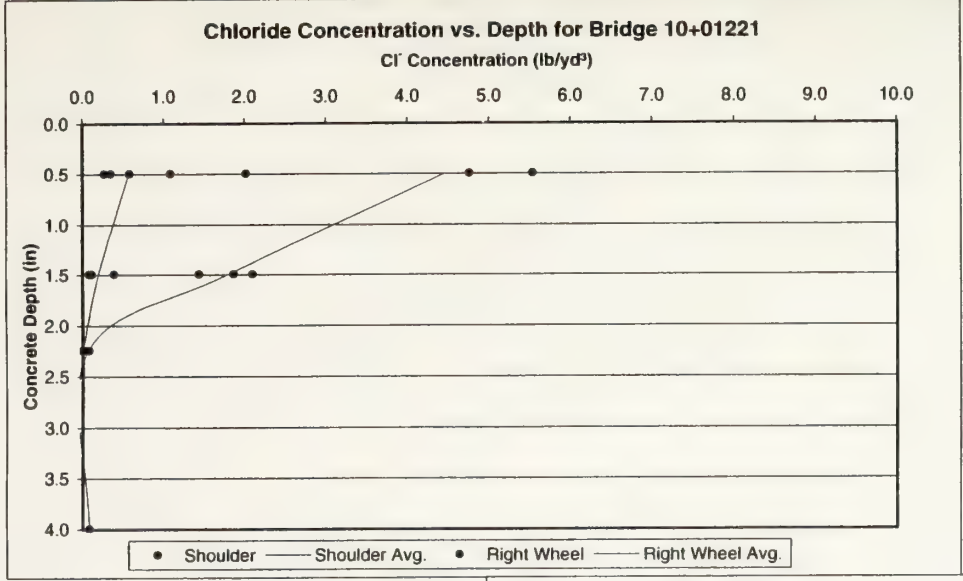


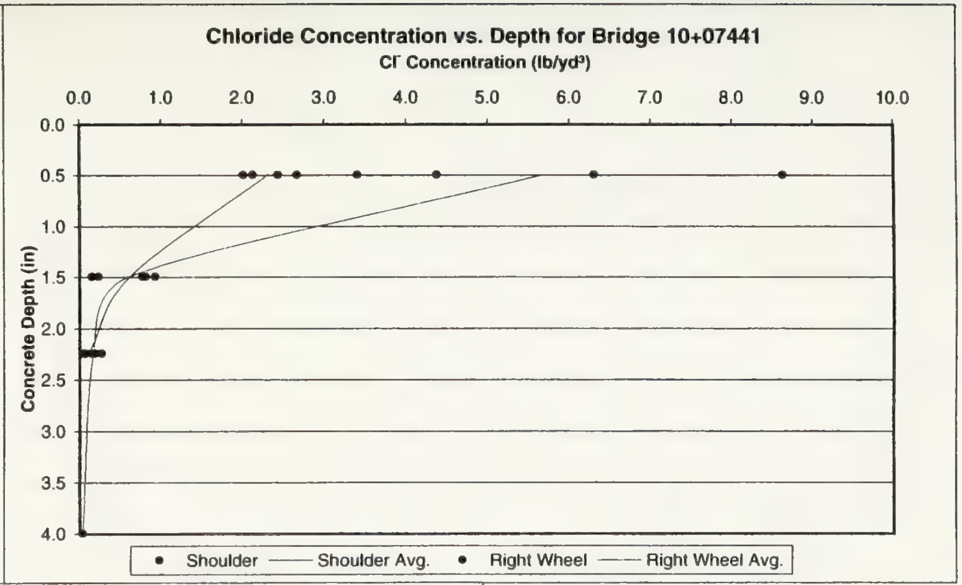
Chloride Concentration vs. Depth for Bridge 05+01481

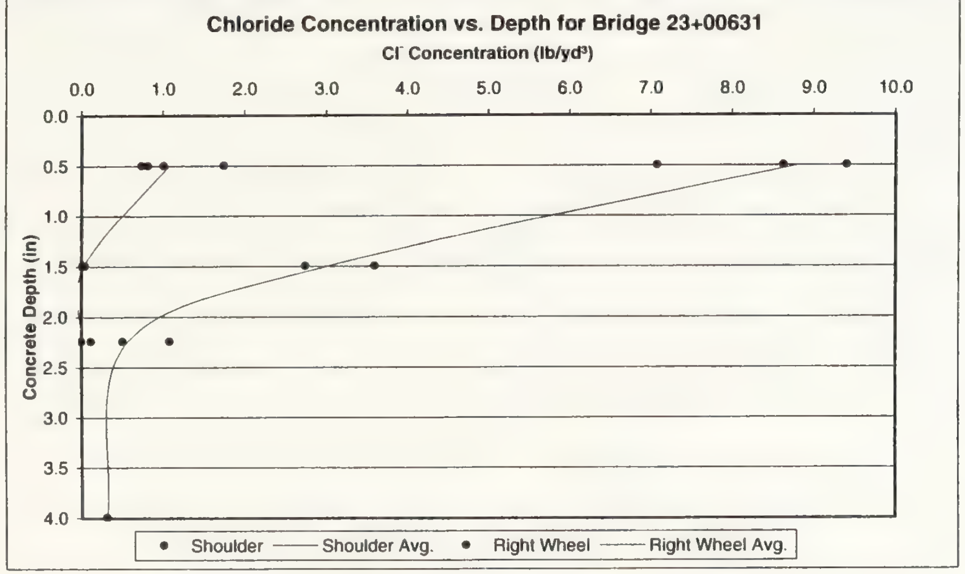


Chloride Concentration vs. Depth for Bridge 06+05481

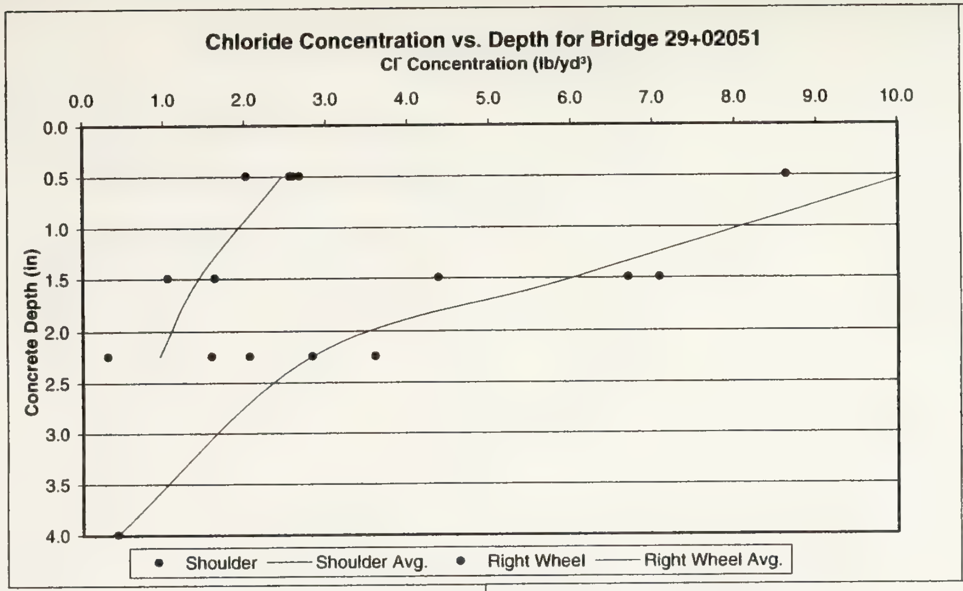
Chloride Concentration Profiles (corrected) for $MgCl_2$ Treated Bridges

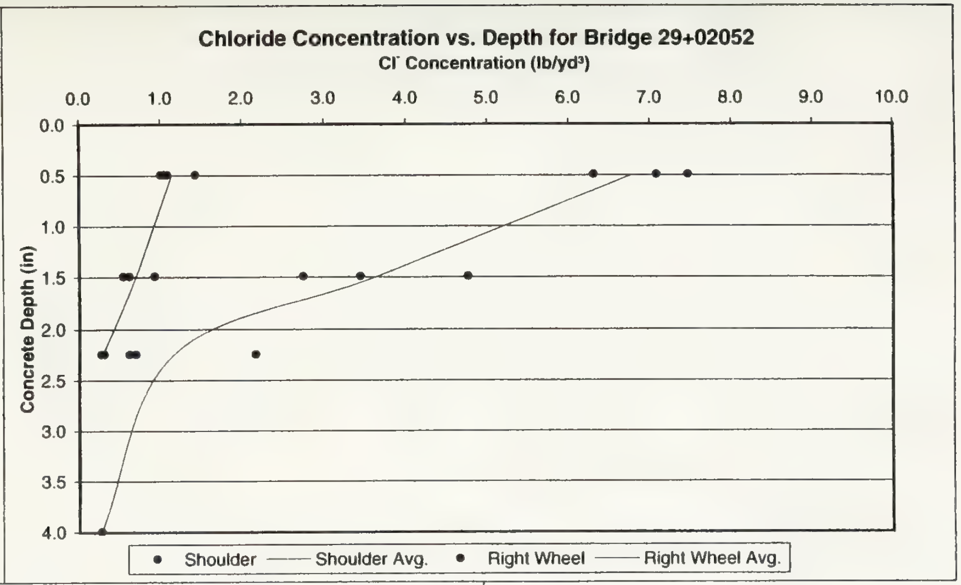

Chloride Concentration vs. Depth for Bridge 10+01221

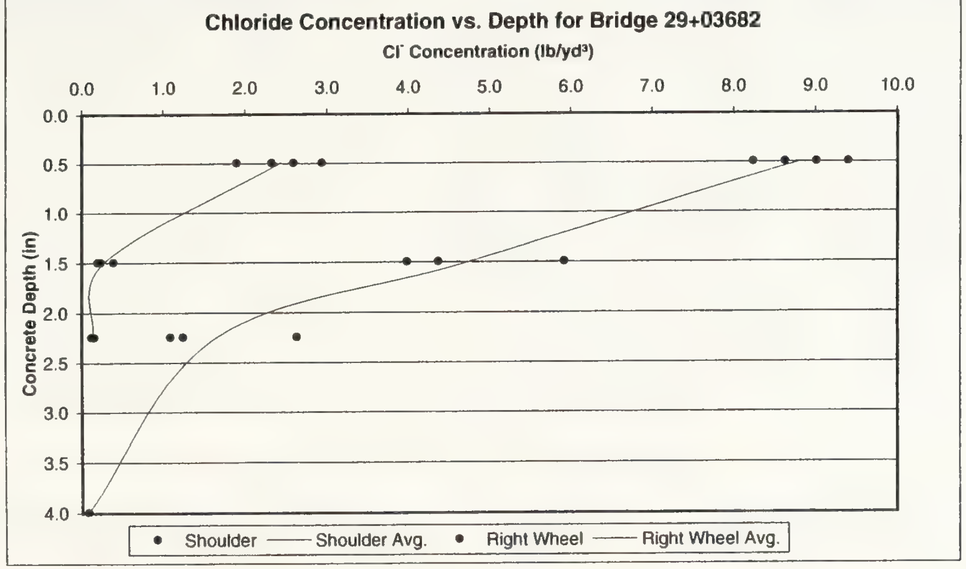

Chloride Concentration vs. Depth for Bridge 10+07441


Chloride Concentration vs. Depth for Bridge 23+00631

Chloride Concentration Profiles (corrected) for $MgCl_2$ Treated Bridges

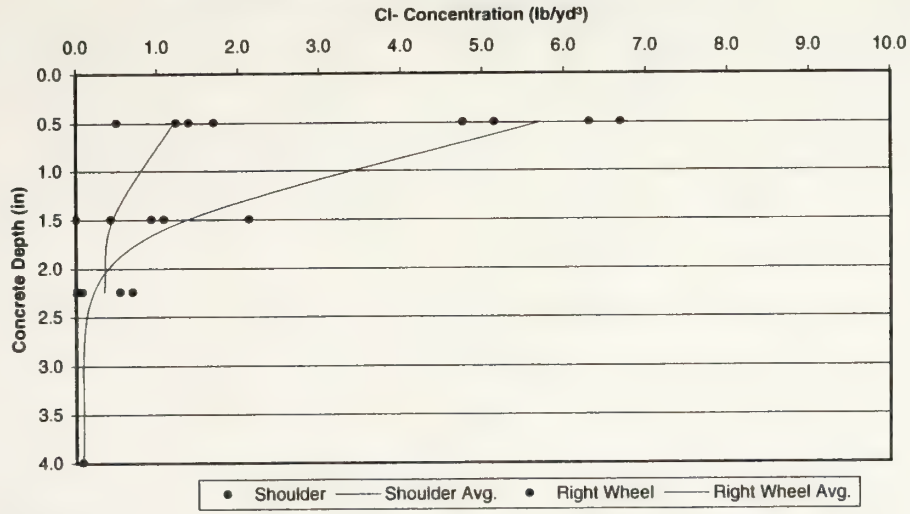

Chloride Concentration vs. Depth for Bridge 29+02051


Chloride Concentration vs. Depth for Bridge 29+02052

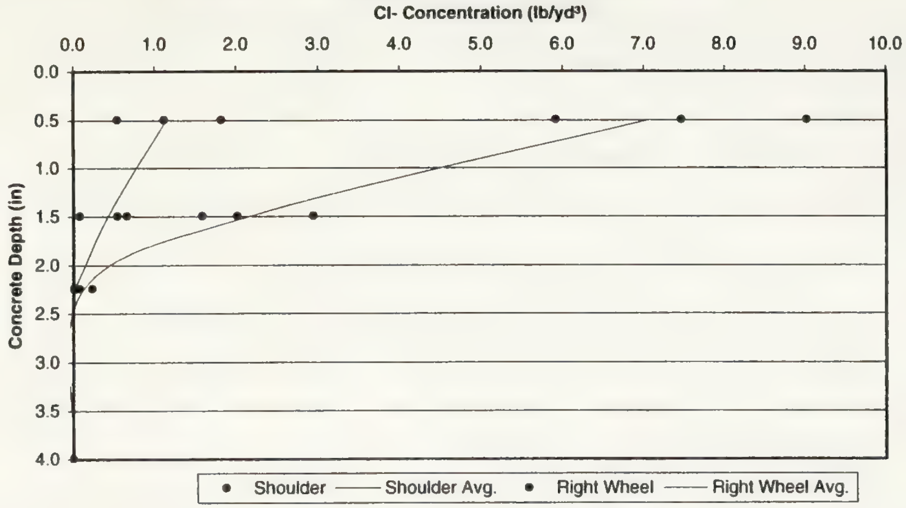

Chloride Concentration vs. Depth for Bridge 29+03682

Chloride Concentration Profiles (corrected) for NaCl Treated Bridges

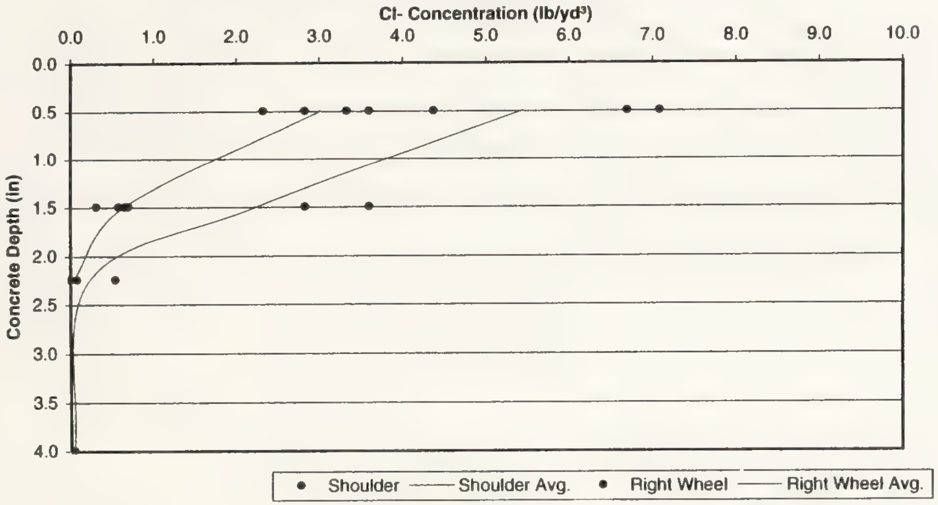
Chloride Concentration vs. Depth for Bridge 34+02081



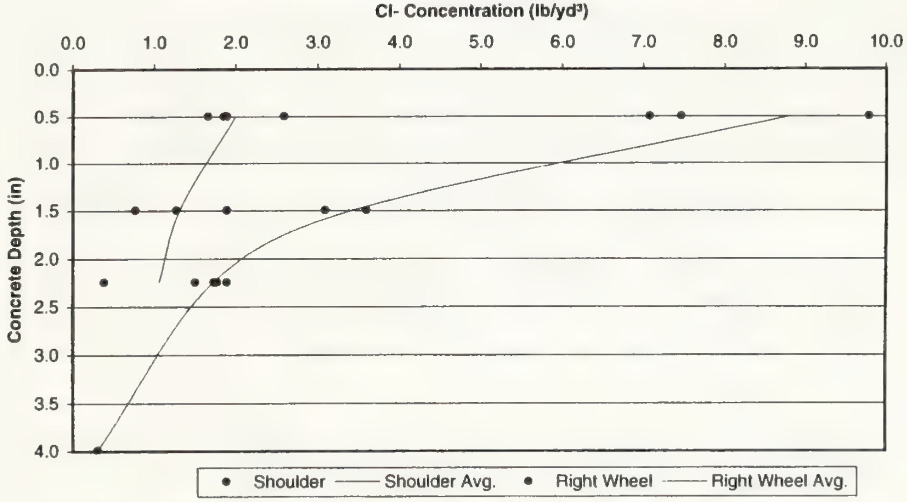
Chloride Concentration vs. Depth for Bridge 34+02082



Chloride Concentration vs. Depth for Bridge 39+08052

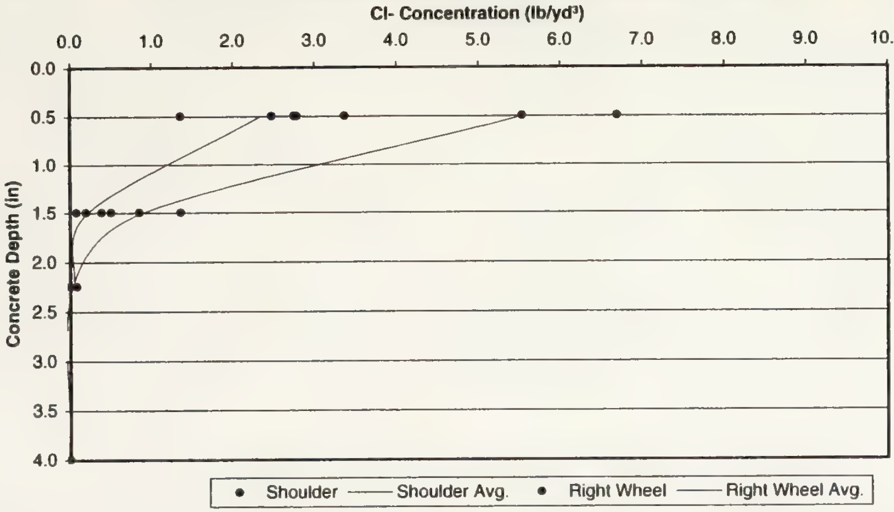


Chloride Concentration vs. Depth for Bridge 39+09911

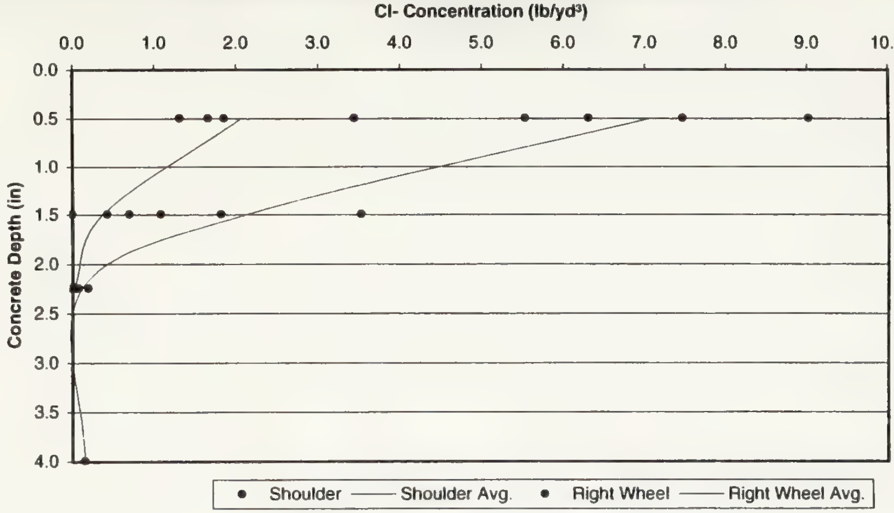


Chloride Concentration Profiles (corrected) for NaCl Treated Bridges

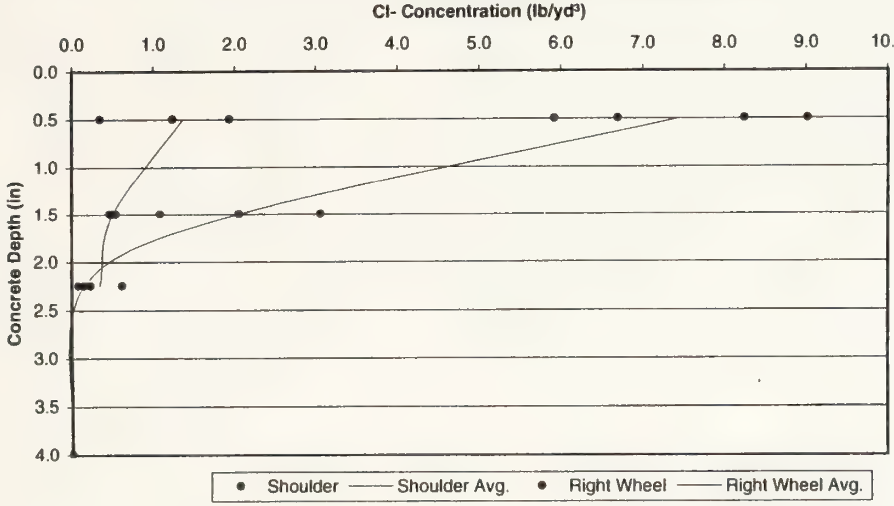
Chloride Concentration vs. Depth for Bridge 39+09912



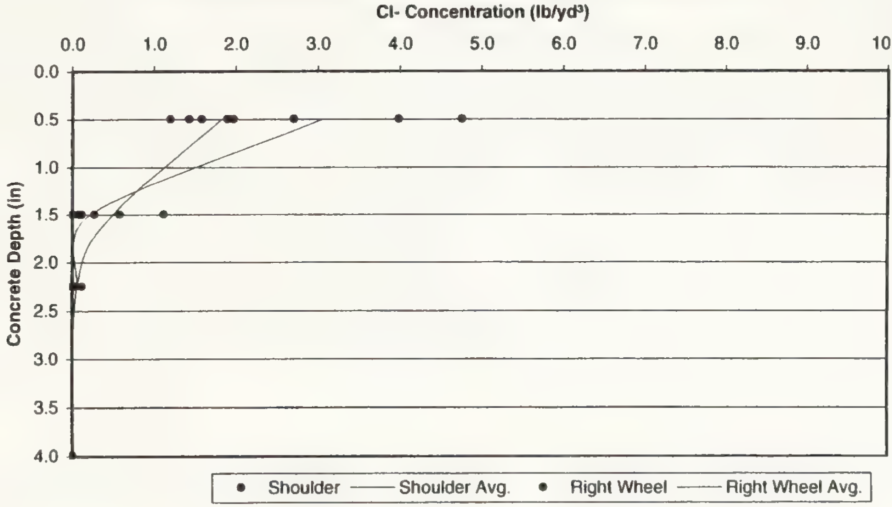
Chloride Concentration vs. Depth for Bridge 42+09191



Chloride Concentration vs. Depth for Bridge 58+05501

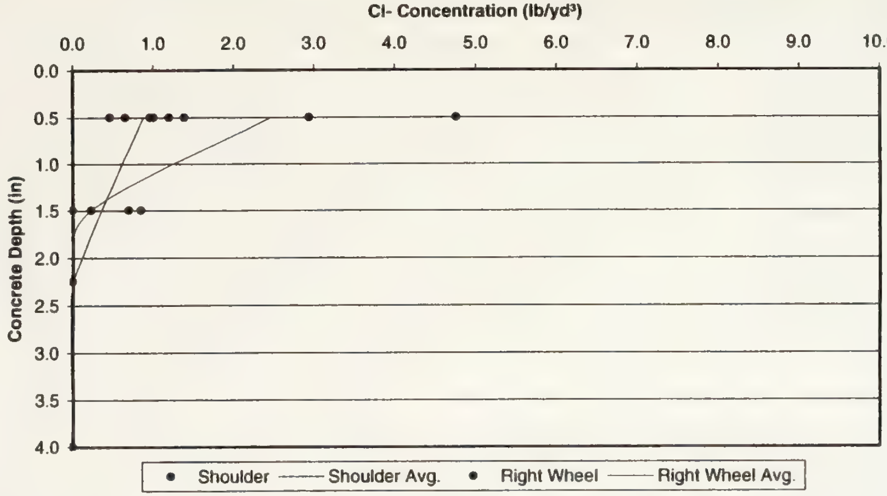


Chloride Concentration vs. Depth for Bridge 58+05502

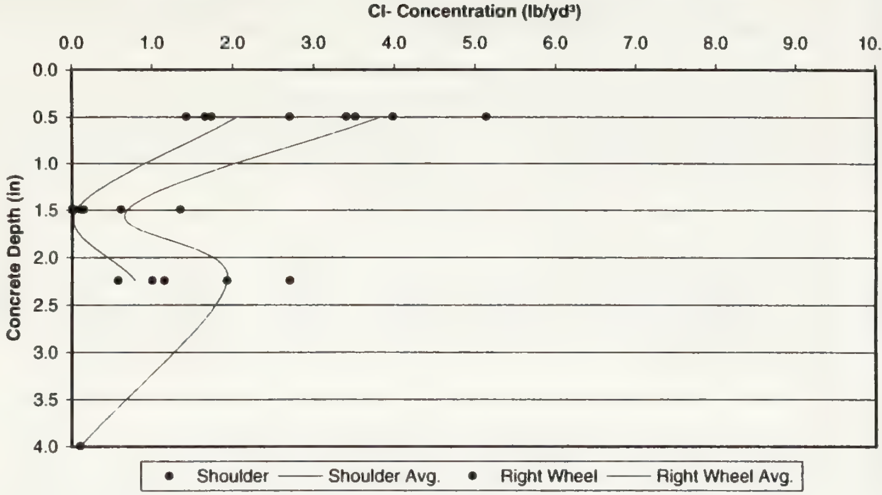


Chloride Concentration Profiles (corrected) for Rehabilitated Bridges

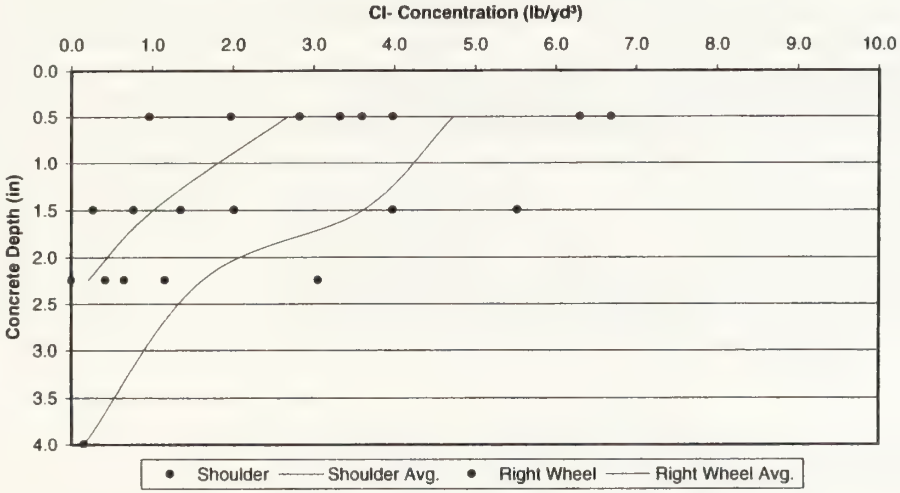
Chloride Concentration vs. Depth for Bridge 45+01802 (Epoxy)



Chloride Concentration vs. Depth for Bridge 53+07232 (Latex)



Chloride Concentration vs. Depth for Bridge 57+04722 (Epoxy)



Diffusion Coefficient Summary for $MgCl_2$ Treated Bridges

Bridge No.	Shoulder			Right Wheel		
	D_c 0.5"-1.5" (in²/yr)	D_c 0.5"-2.25" (in²/yr)	Average D_c (in²/yr)	D_c 0.5"-1.5" (in²/yr)	D_c 0.5"-2.25" (in²/yr)	Average D_c (in²/yr)
01+ 09821	0.056	0.040	***0.048***	0.127	0.078	***0.103***
	0.048	0.025	***0.036***	0.235	0.075	***0.155***
	0.020		***0.020***	0.103	0.042	***0.072***
05 + 01481	0.026	0.028	***0.027***	0.041	0.016	***0.028***
	0.036	0.027	***0.032***	0.085	0.021	***0.053***
	0.071		***0.071***	0.200	0.040	***0.120***
06 + 05481	0.024	0.086	***0.055***	0.089	0.084	***0.086***
	0.015	0.034	***0.024***	0.048	0.037	***0.043***
	0.054		***0.054***	0.070	0.024	***0.047***
10 + 01221	0.039	0.026	***0.033***	0.074	0.021	***0.047***
	0.035	0.023	***0.029***	0.137	0.018	***0.077***
	0.067		***0.067***	0.052	0.022	***0.037***
10 + 07441	0.056	0.028	***0.042***	0.032	0.019	***0.025***
	0.064	0.035	***0.049***	0.020	0.024	***0.022***
	0.017		***0.017***	0.017	0.041	***0.029***
23 + 00631	0.015	0.021	***0.018***	0.074	0.051	***0.062***
	0.009	0.020	***0.015***	0.076	0.022	***0.049***
	0.013		***0.013***	0.046	0.033	***0.040***
29 + 02051	0.080	0.052	***0.066***	0.127	0.091	***0.109***
	0.260	0.525	***0.393***	0.309	0.139	***0.224***
	0.983		***0.983***	0.195	0.095	***0.145***
29 + 02052	0.221	0.103	***0.162***	0.452	0.141	***0.297***
	0.135	0.117	***0.126***	0.076	0.043	***0.060***
	0.274		***0.274***	0.154	0.050	***0.102***
29 + 03682	0.018	0.035	***0.026***	0.105	0.057	***0.081***
	0.035	0.037	***0.036***	0.115	0.056	***0.085***
	0.021		***0.021***	0.242	0.108	***0.175***

Diffusion Coefficient Summary for NaCl Treated Bridges

Reid Crowther

PROJECT NUMBER: 77054-00-

Bridge No.	Shoulder			Right Wheel		
	D_c 0.5"-1.5" (in^2/yr)	D_c 0.5"-2.25" (in^2/yr)	Average D_c (in^2/yr)	D_c 0.5"-1.5" (in^2/yr)	D_c 0.5"-2.25" (in^2/yr)	Average D_c (in^2/yr)
34 + 02081	0.550	0.381	***0.466***	0.060	0.043	***0.052***
	0.010	0.023	***0.017***	0.029	0.020	***0.024***
	0.054		***0.054***	0.031	0.018	***0.025***
34 + 02082	0.014	0.016	***0.015***	0.045	0.030	***0.038***
	0.114	0.029	***0.071***	0.058	0.019	***0.038***
	0.193		***0.193***	0.046	0.019	***0.033***
39 + 08052	0.053	0.028	***0.041***	0.082	0.020	***0.051***
	0.034	0.014	***0.024***	0.019	0.024	***0.022***
	0.035		***0.035***	0.148	0.042	***0.095***
39 + 09911	0.486	0.705	***0.595***	0.110	0.078	***0.094***
	0.349	0.080	***0.215***	0.056	0.075	***0.066***
	0.105		***0.105***	0.059	0.065	***0.062***
39 + 09912	0.017	0.015	***0.016***	0.017	0.013	***0.017***
	0.028	0.028	***0.028***	0.042	0.025	***0.027***
	0.016		***0.016***	0.043		***0.034***
42 + 09191	0.039	0.024	***0.032***	0.059	0.021	***0.040***
	0.006	0.014	***0.010***	0.030	0.020	***0.025***
	0.087		***0.087***	0.076	0.024	***0.050***
58 + 05501	0.048	0.030	***0.039***	0.054	0.020	***0.037***
	0.040	0.128	***0.084***	0.032	0.030	***0.031***
	0.081		***0.081***	0.070	0.023	***0.047***
58 + 05502	0.021	0.018	***0.020***	0.026	0.012	***0.019***
	0.025	0.036	***0.031***	0.015	0.025	***0.020***
	0.084		***0.084***	0.007	0.016	***0.012***

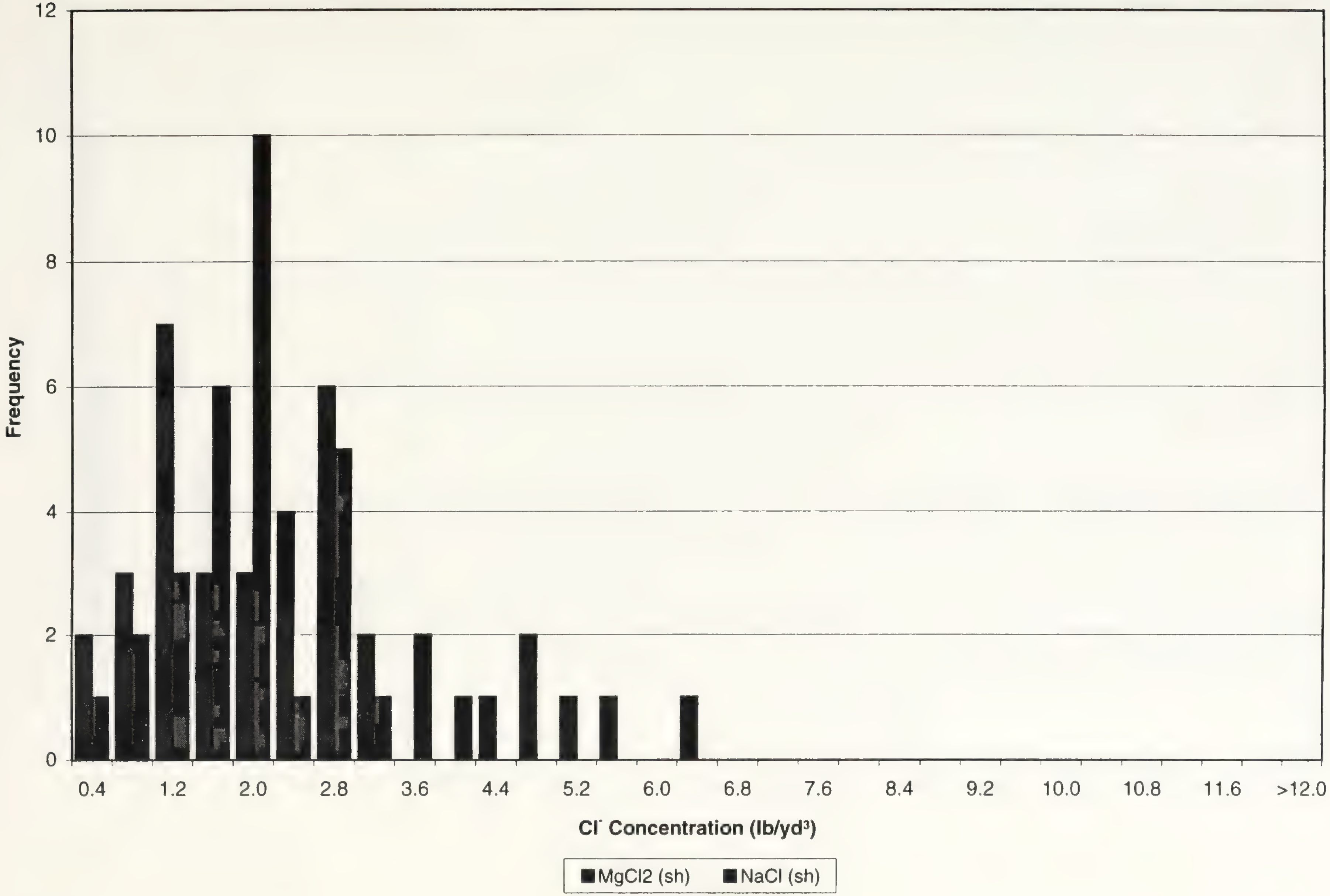
Descriptive Measures for Calculated Diffusion Coefficients

	D_c Along Shoulder (in^2/yr)			D_c Along Right Wheel (in^2/yr)		
	0"-1.5" Depth Interval	0"-2.25" Depth Interval	Average	0"-1.5" Depth Interval	0"-2.25" Depth Interval	Average
$MgCl_2$ Bridges						
No. of data points (n)	27	18	27	27	27	27
Mean (μ)	0.100	0.070	0.101	0.122	0.054	0.088
Standard Deviation (σ)	0.191	0.117	0.196	0.098	0.036	0.065
Coeff. Of Variation (V)	1.91	1.67	1.93	0.80	0.68	0.74
NaCl Bridges						
No. of data points (n)	24	16	24	24	23	24
Mean (μ)	0.104	0.098	0.098	0.051	0.030	0.040
Standard Deviation (σ)	0.148	0.186	0.144	0.032	0.019	0.022
Coeff. Of Variation (V)	1.42	1.89	1.47	0.63	0.63	0.55

Descriptive Measures for Ln-Transformed Diffusion Coefficients

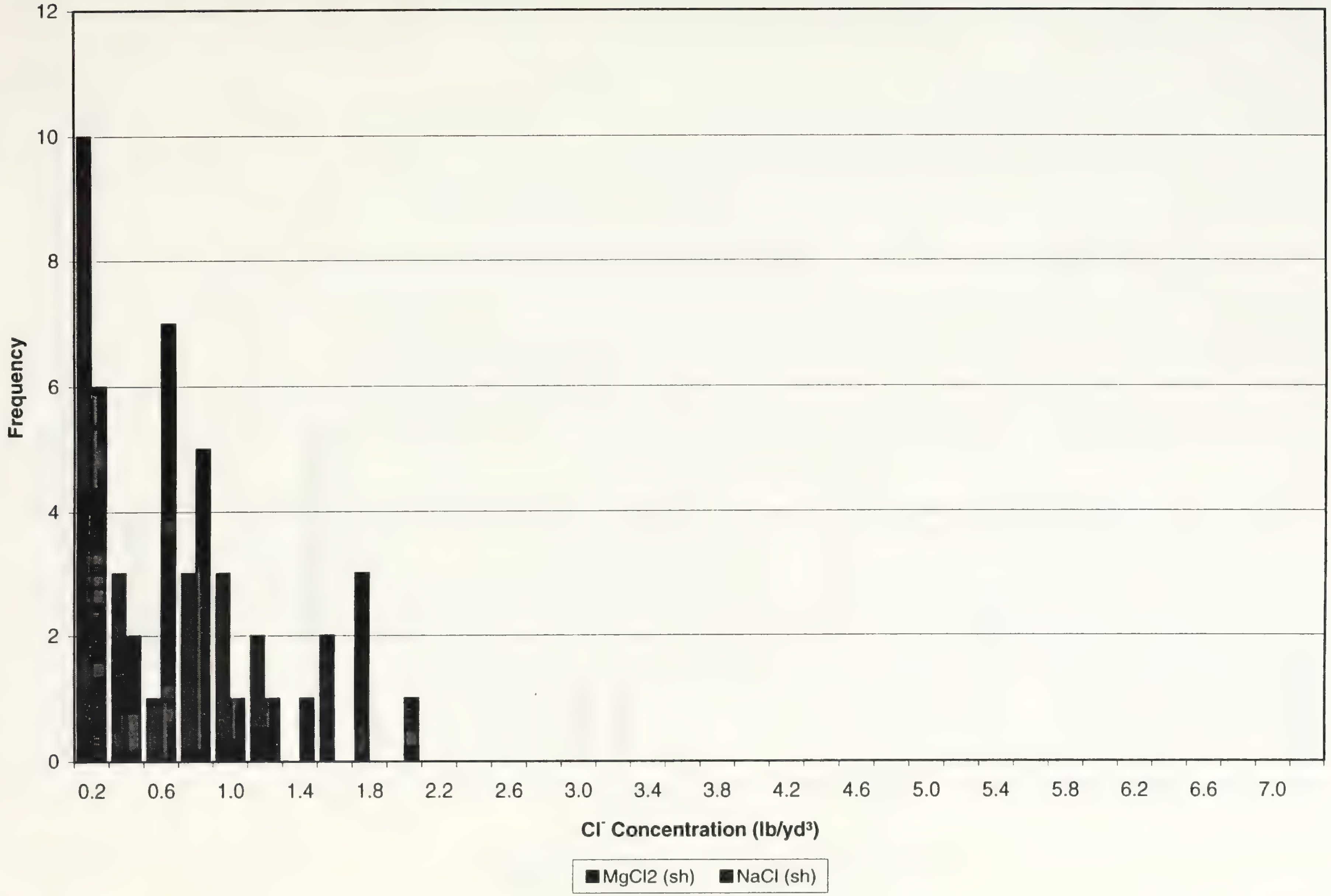
	Ln (D_c) Along Shoulder			Ln (D_c) Along Right Wheel		
	0"-1.5" Depth Interval	0"-2.25" Depth Interval	Average	0"-1.5" Depth Interval	0"-2.25" Depth Interval	Average
$MgCl_2$ Bridges						
No. of data points (n)	-	-	27	-	-	27
Mean (μ)	-	-	-3.025	-	-	-2.655
Standard Deviation (σ)	-	-	1.034	-	-	0.674
Coeff. Of Variation (V)	-	-	0.34	-	-	0.25
NaCl Bridges						
No. of data points (n)	-	-	24	-	-	24
Mean (μ)	-	-	-2.971	-	-	-3.354
Standard Deviation (σ)	-	-	1.083	-	-	0.522
Coeff. Of Variation (V)	-	-	0.36	-	-	0.16

Frequency Distribution of Cl^- Levels at the 0.5" Test Depth (shoulder)



PROJECT NUMBER: 77054-00-3

Frequency Distribution of Cl⁻ Levels at the 1.5" Test Depth (shoulder)



Frequency Distribution of Cl⁻ Levels at the 2.25" Test Depth (shoulder)

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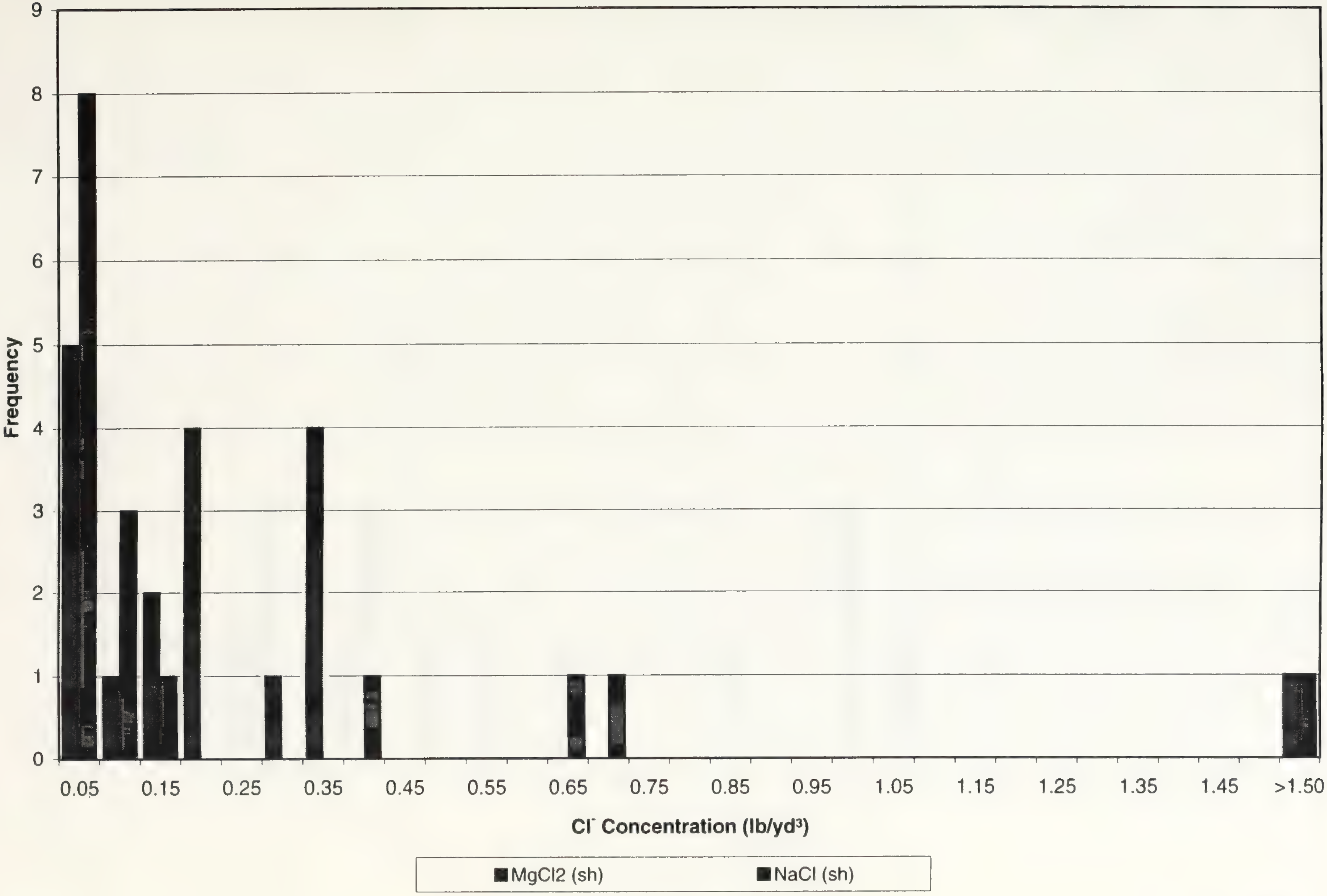
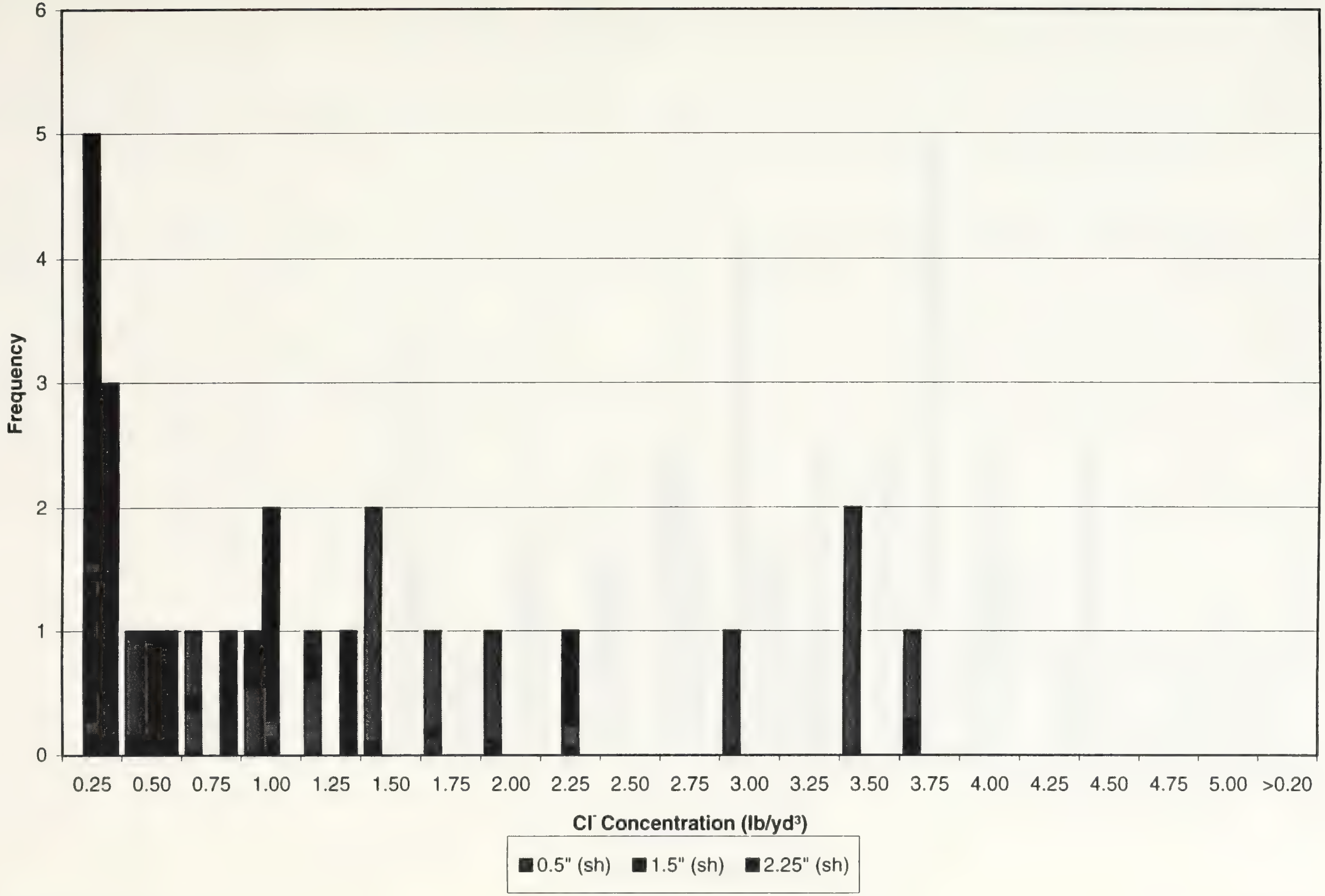


2.25" (sh)
Cl Data Histograms.xls

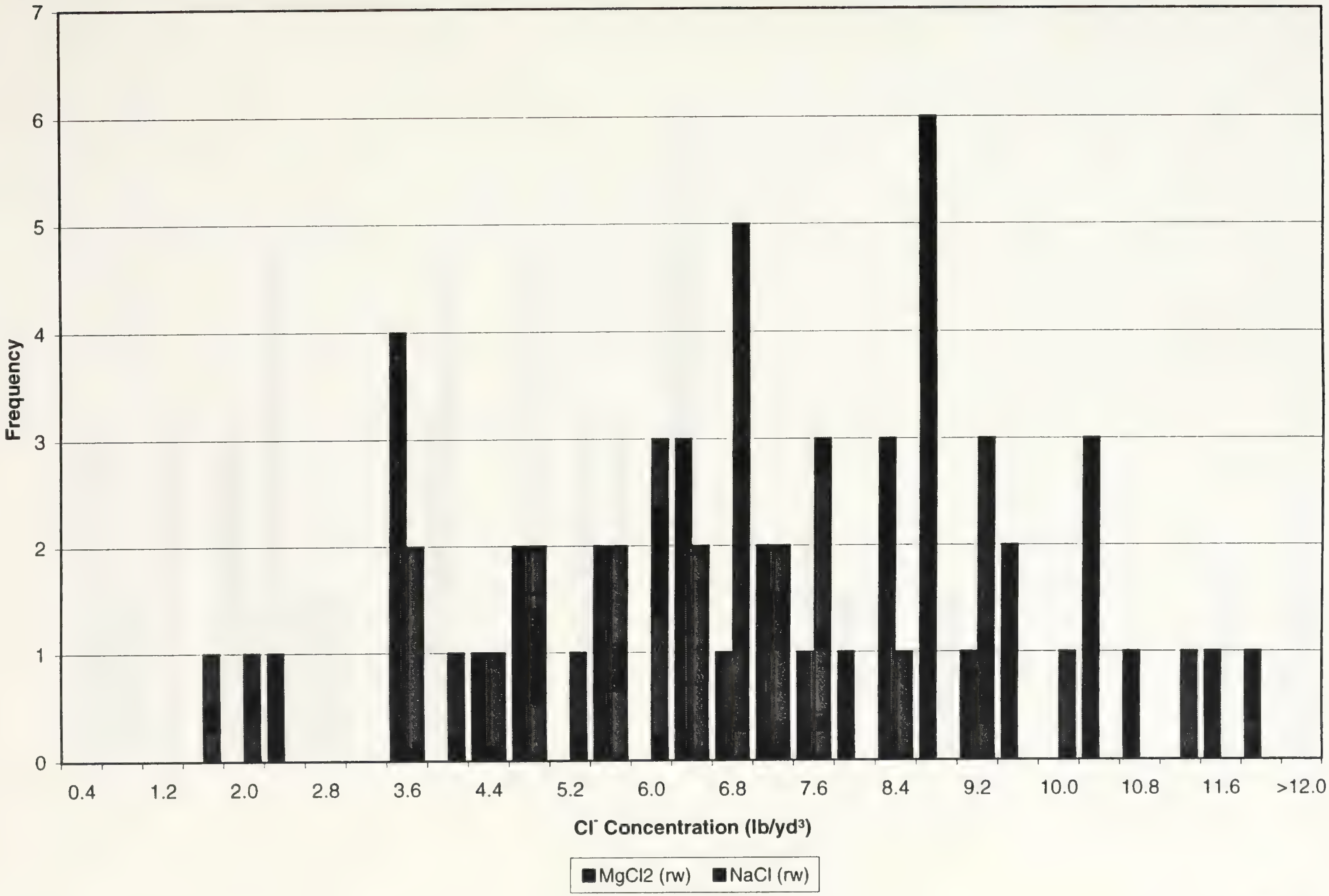
Printed:
03/09/2000

PROJECT NUMBER: 77054-00-3

Frequency Distribution of Cl$^-$ Levels for Rehabilitated Bridges (shoulder)



Frequency Distribution of Cl⁻ Levels at the 0.5" Test Depth (wheel path)



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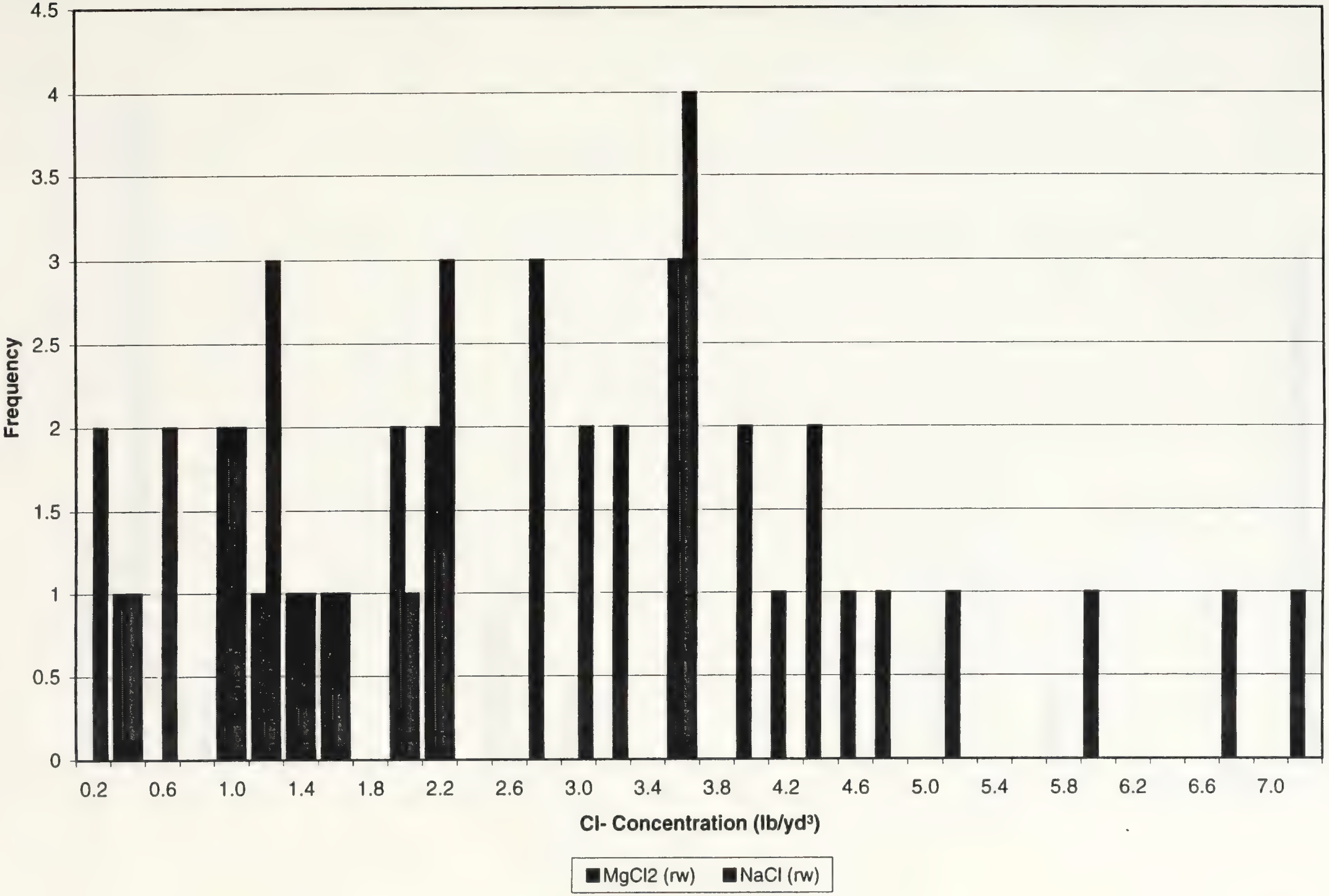
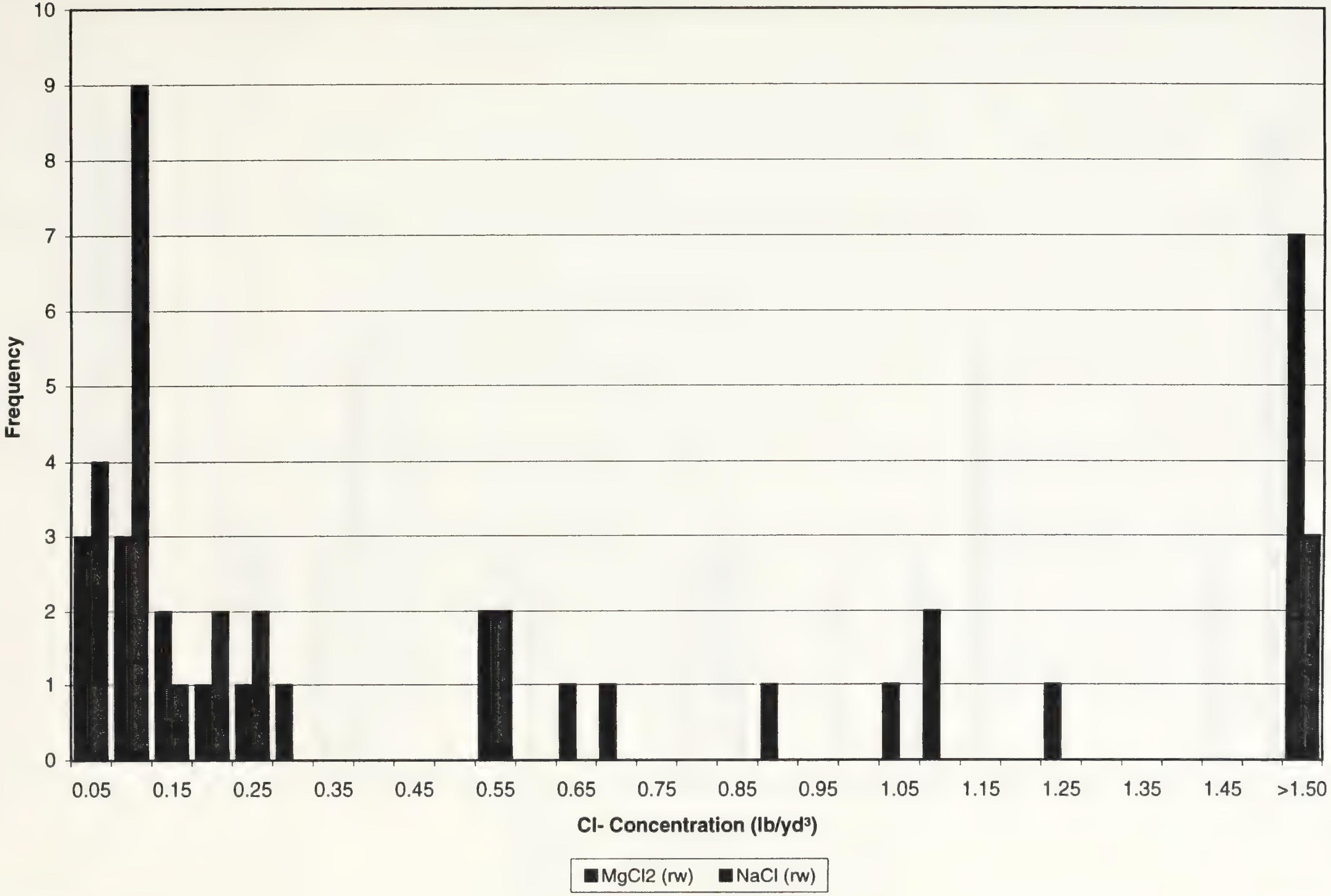
PROJECT NUMBER: 77054-00-3

Frequency Distribution of Cl⁻ Levels at the 1.5" Test Depth (wheel path)



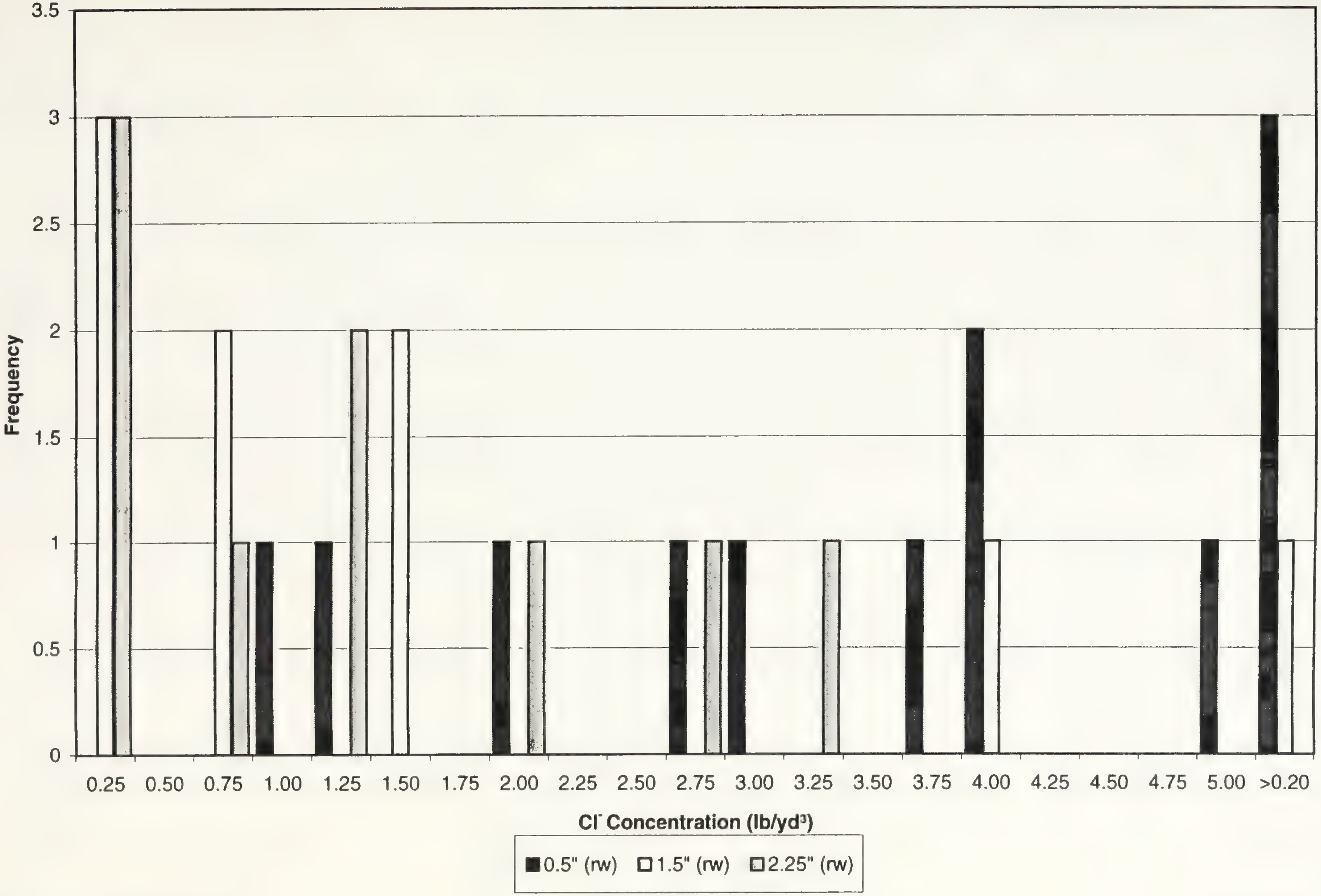
PROJECT NUMBER: 77054-00-3

Frequency Distribution of Cl⁻ Levels at the 2.25" Test Depth (wheel path)



Frequency Distribution of Cl⁻ Levels for Rehabilitated Bridges (wheel path)

Reid Crowther
PROJECT NUMBER: 77054-00-3



Rehab'd NaCl (rw)
Cl Data Histograms.xls

APPENDIX A-8

Printed:
03/09/2000

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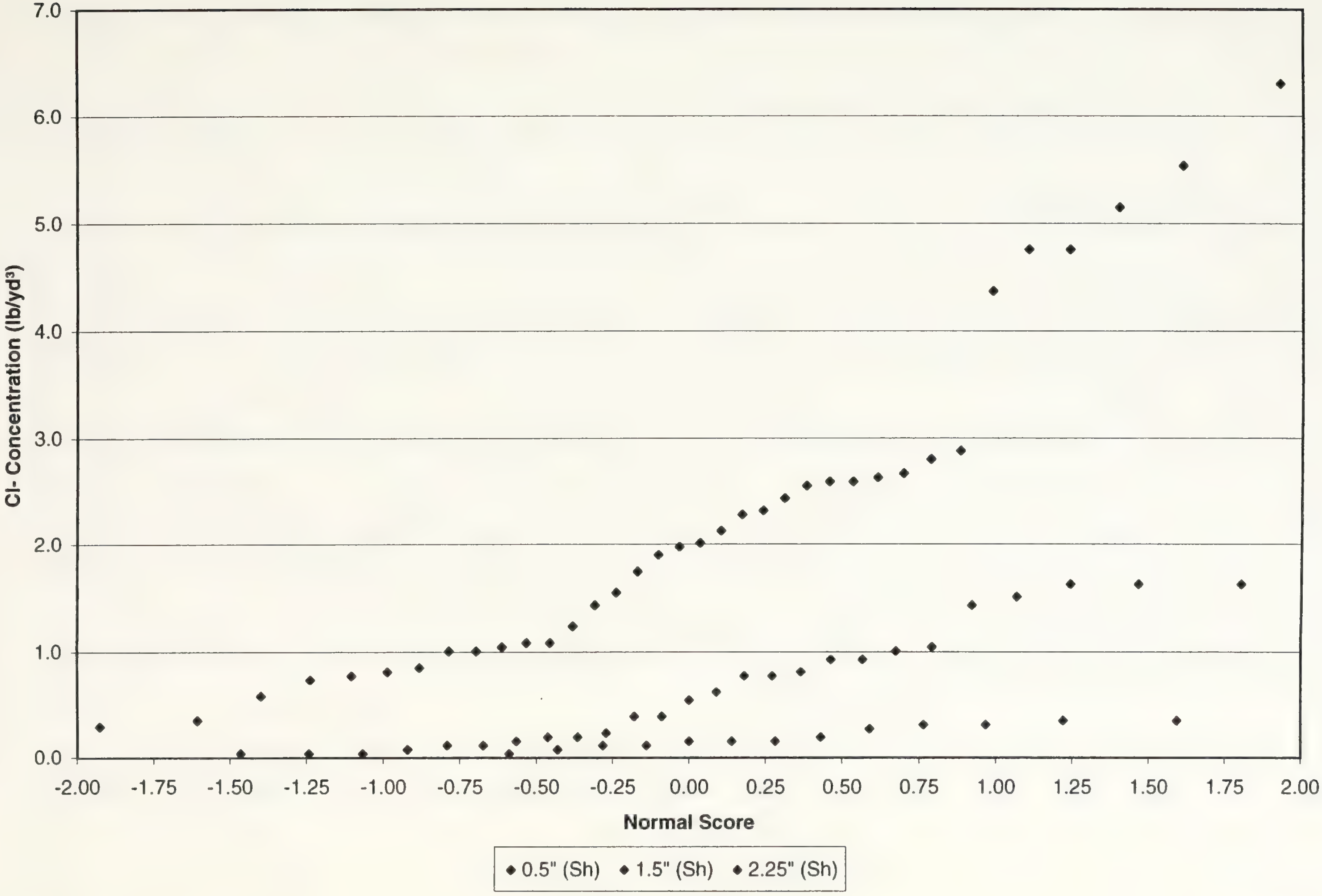
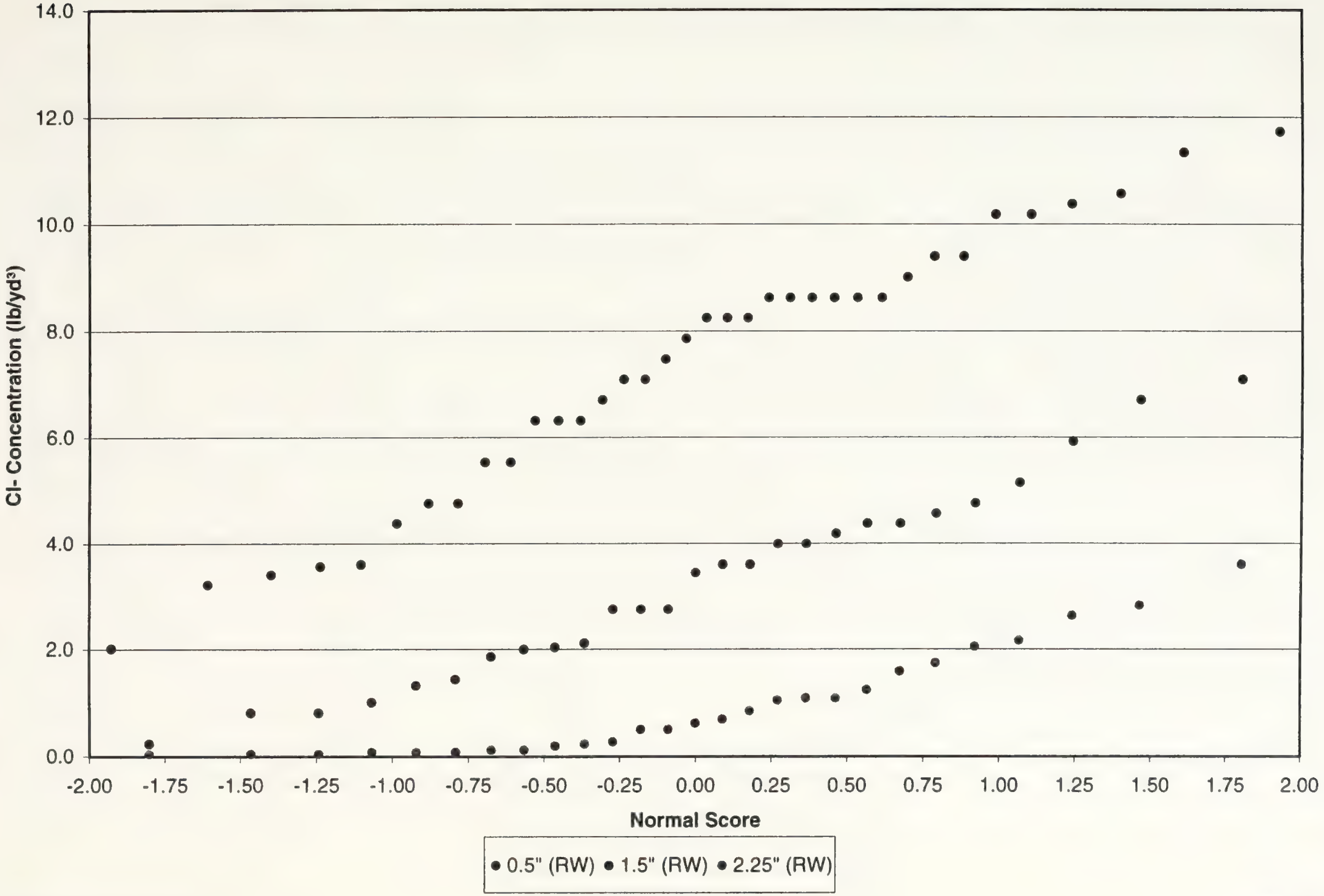
PROJECT NUMBER: 77054-00-3

Normal Score Plot for $MgCl_2$ Bridges (shoulder)

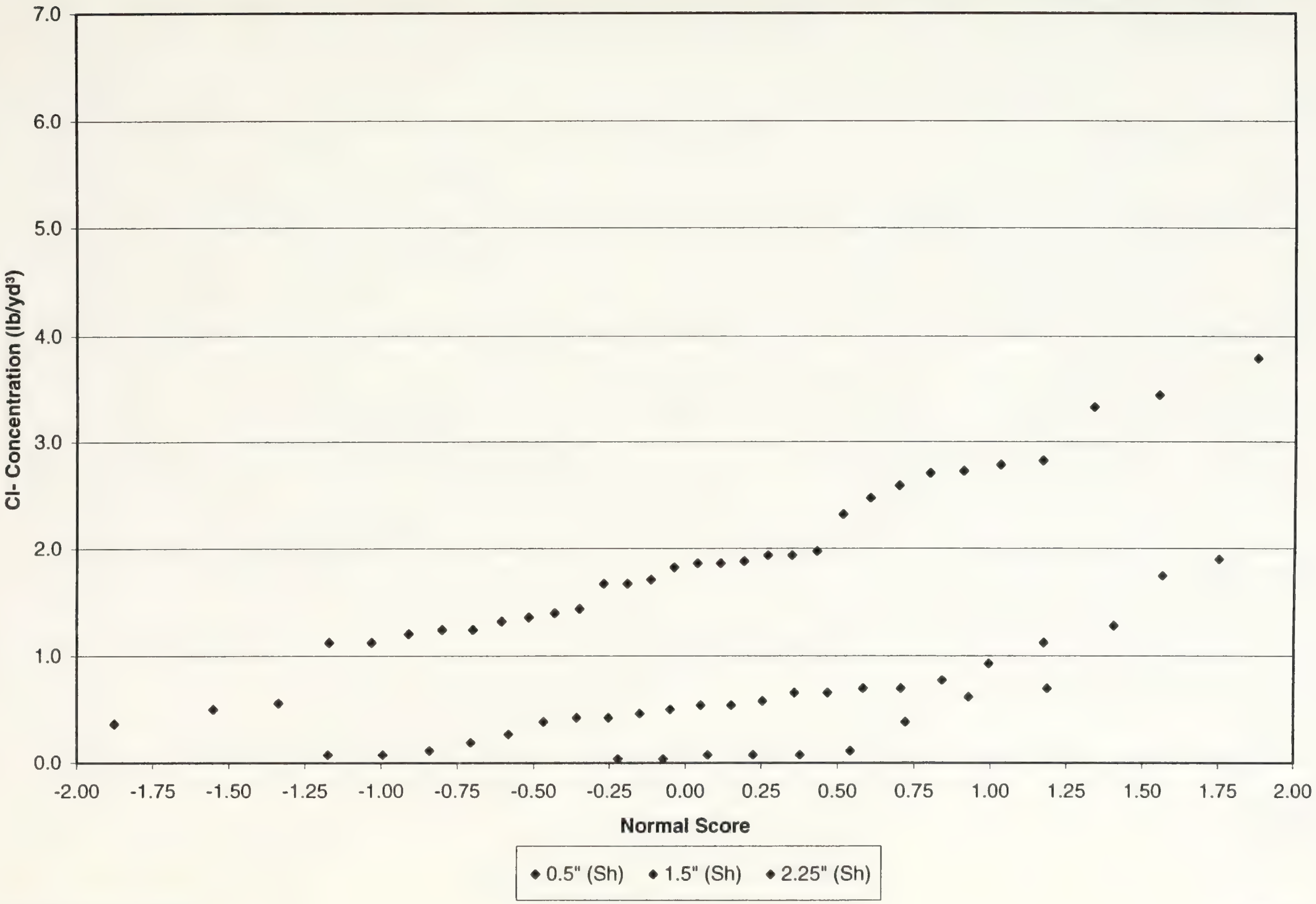


Normal Score Plot for $MgCl_2$ Bridges (right wheel)

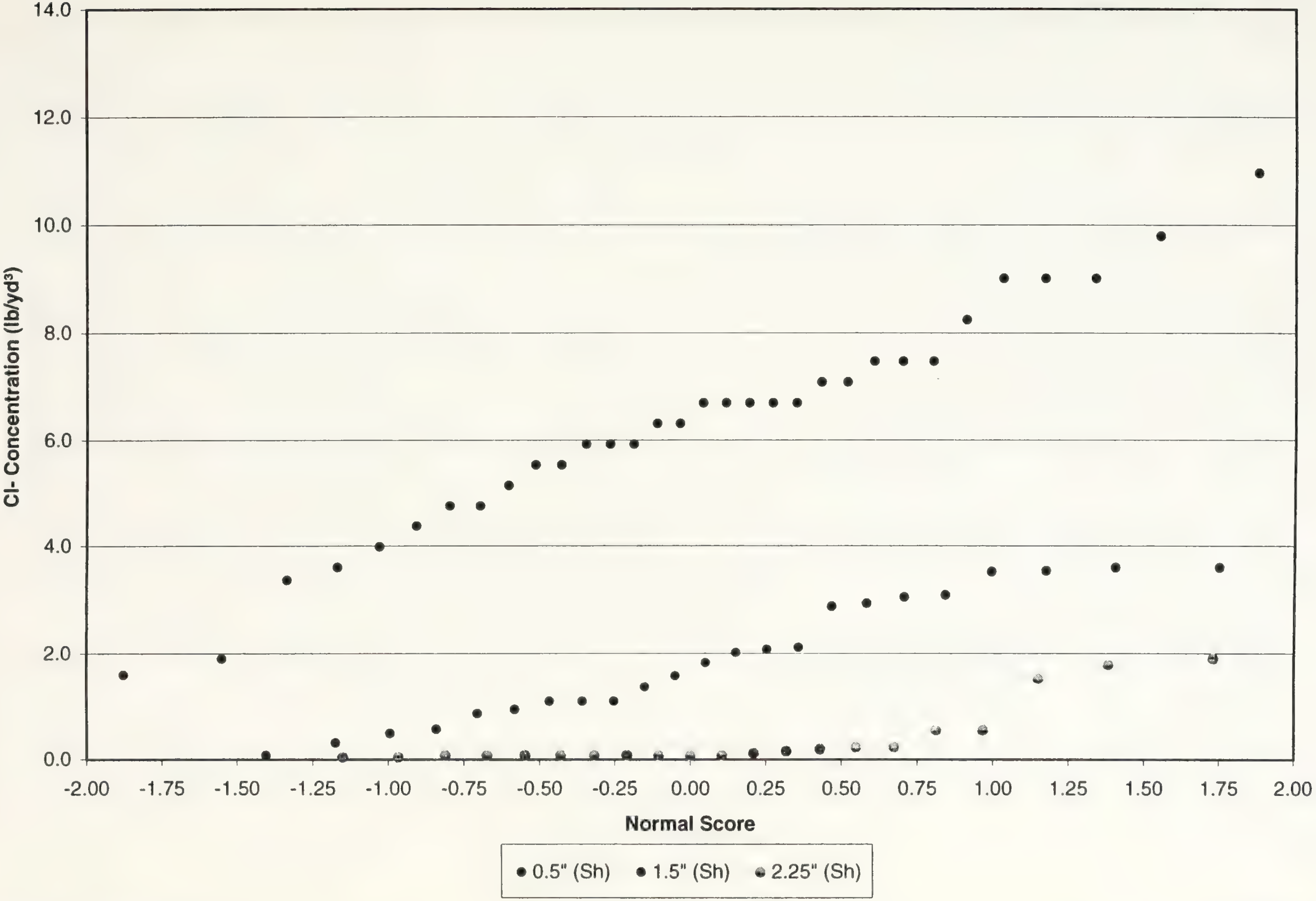


Normal Score Plot for NaCl Treated Bridges (shoulder)

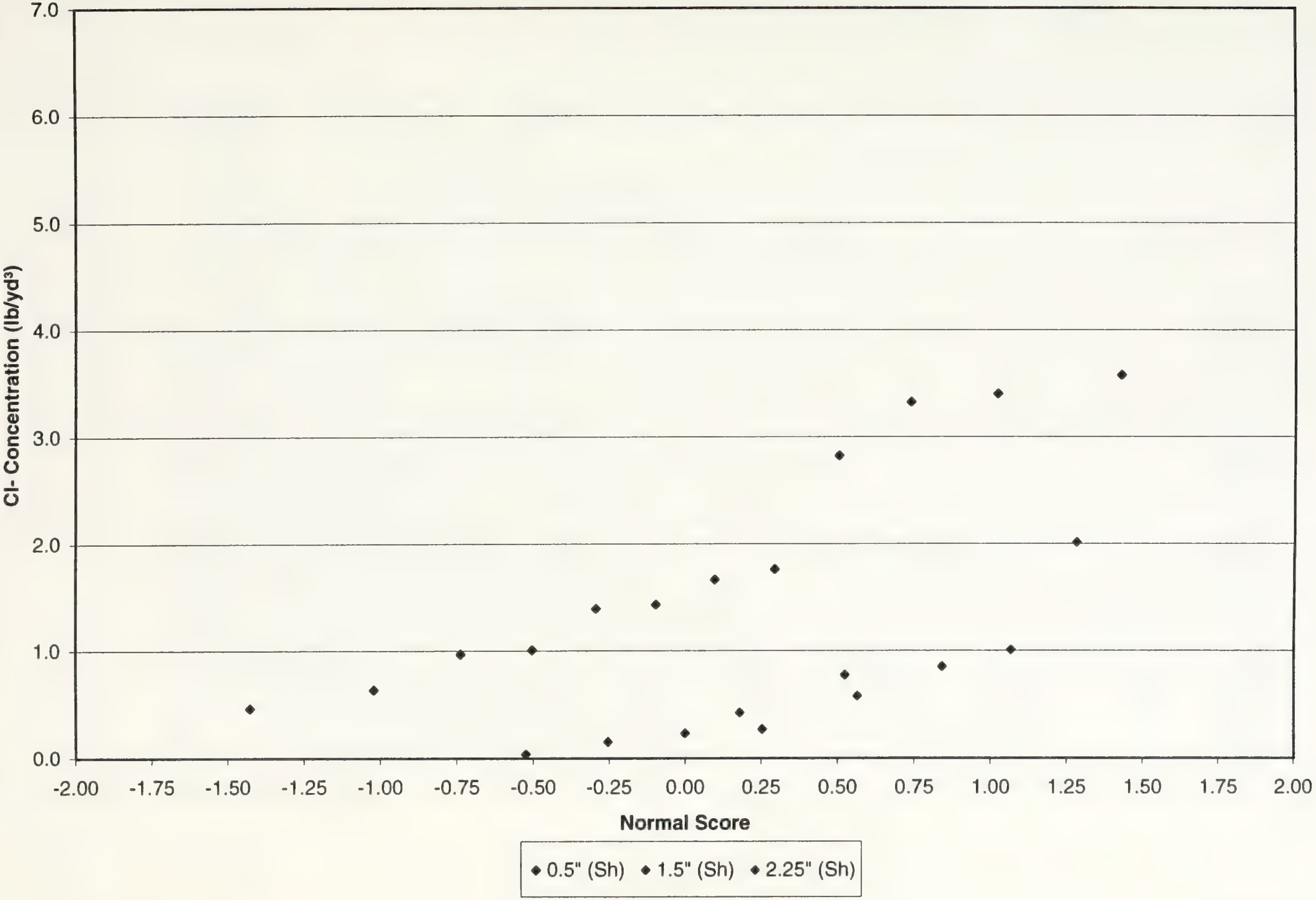
Reid Crowther
PROJECT NUMBER: 77054-00-3



Normal Score Plot for NaCl Treated Bridges (right wheel)

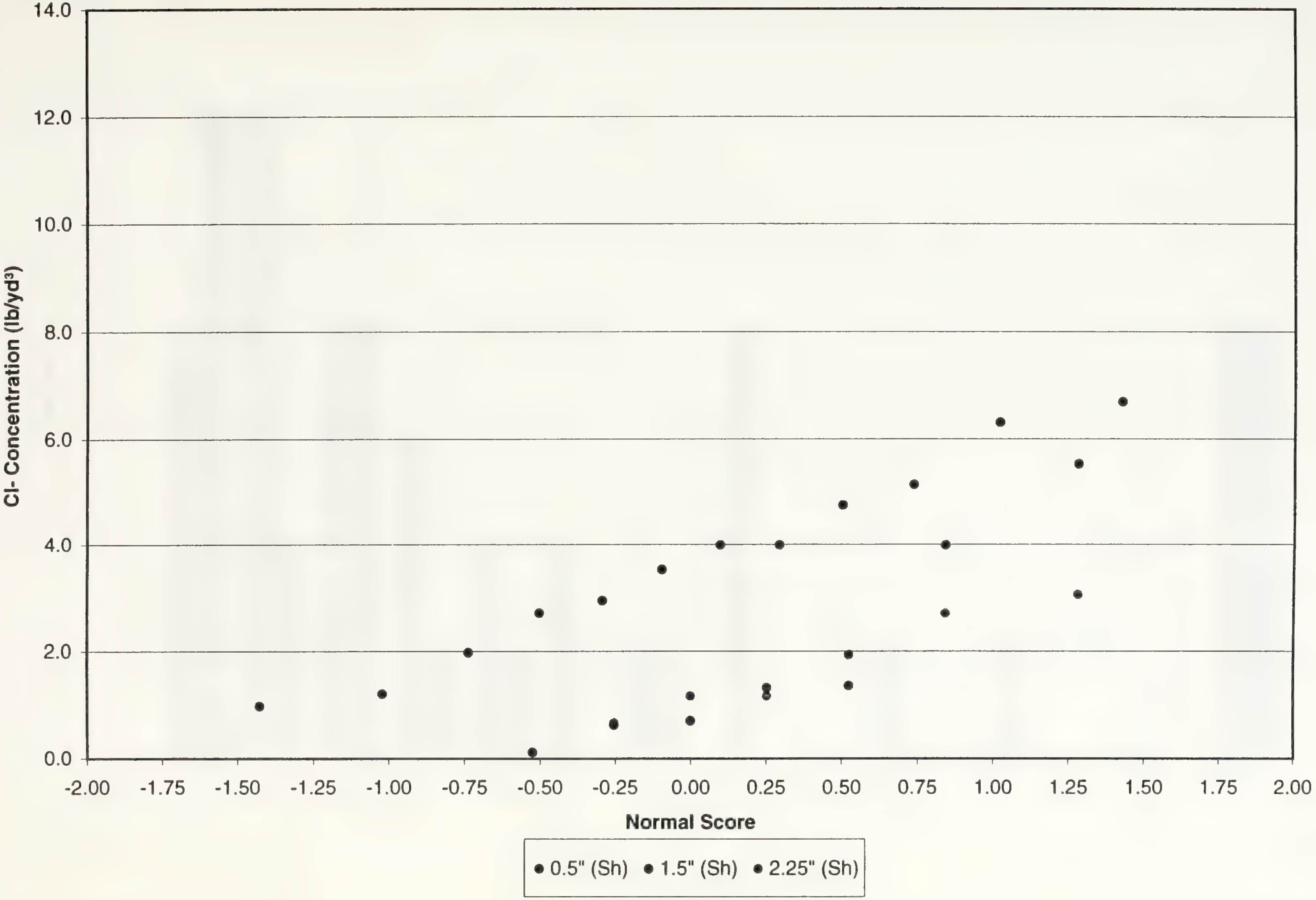


Normal Score Plot for Rehabilitated Bridges (shoulder)



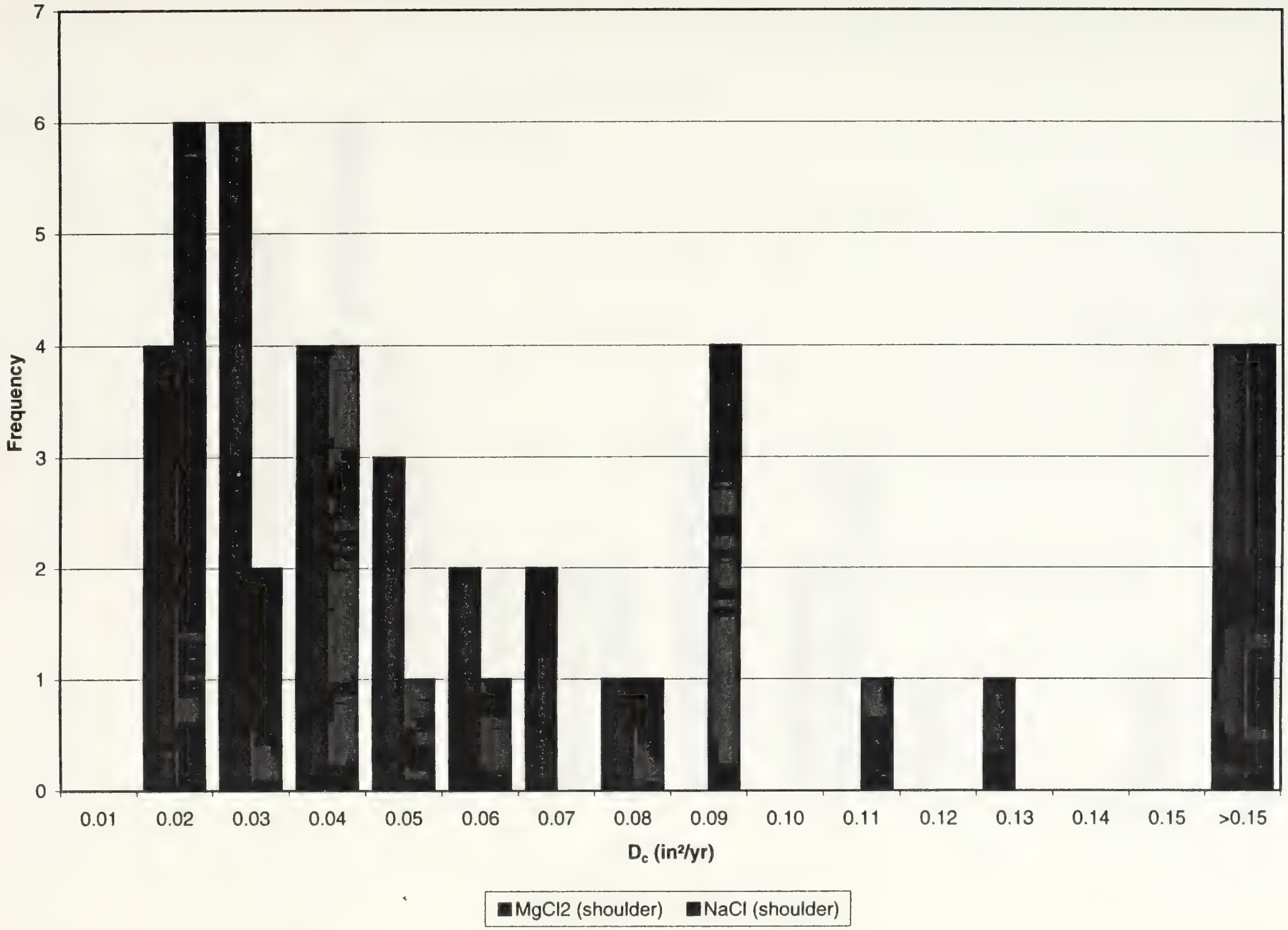
Normal Score Plot for Rehabilitated Bridges (right wheel)

PROJECT NUMBER: 77054-00-3



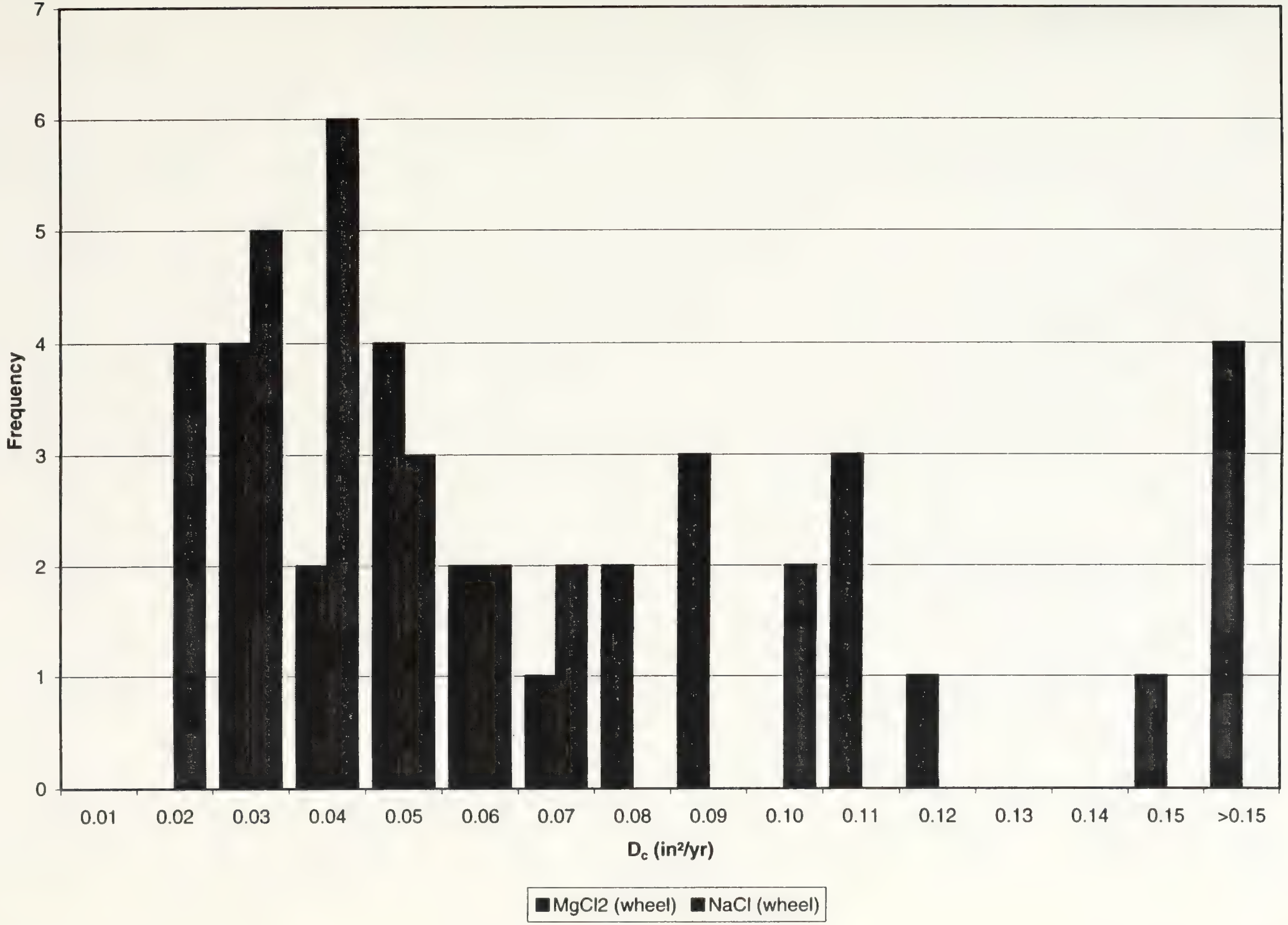
APPENDIX A-9

Frequency Distribution of D_c Values for $MgCl_2$ and NaCl Bridges



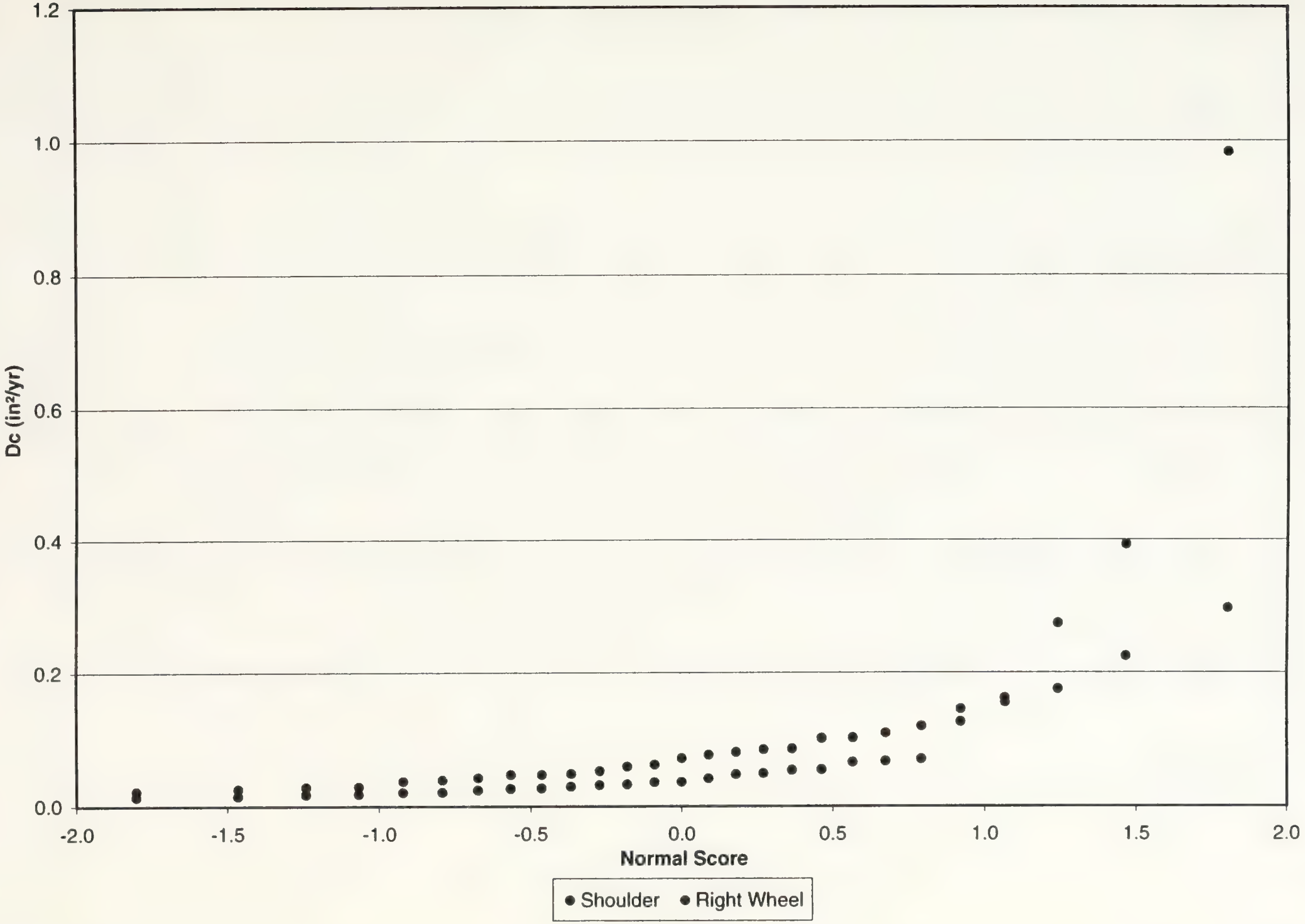
Frequency Distribution of D_c Values for $MgCl_2$ and NaCl Bridges

Reid Crowther
PROJECT NUMBER: 77054-00-3



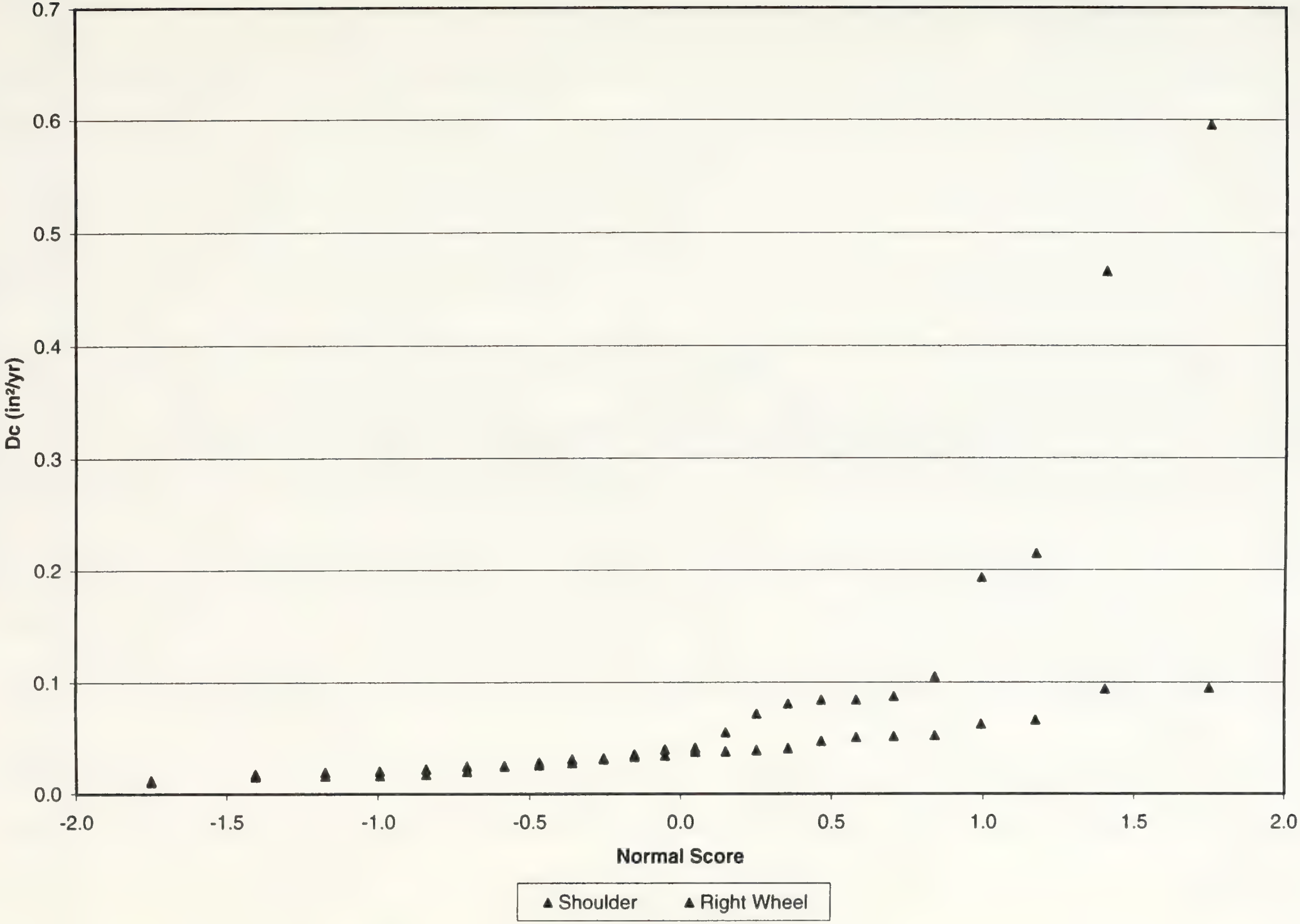
Reid Crowther
PROJECT NUMBER: 77054-00-3

Normal Score Plot for $MgCl_2$ Bridges

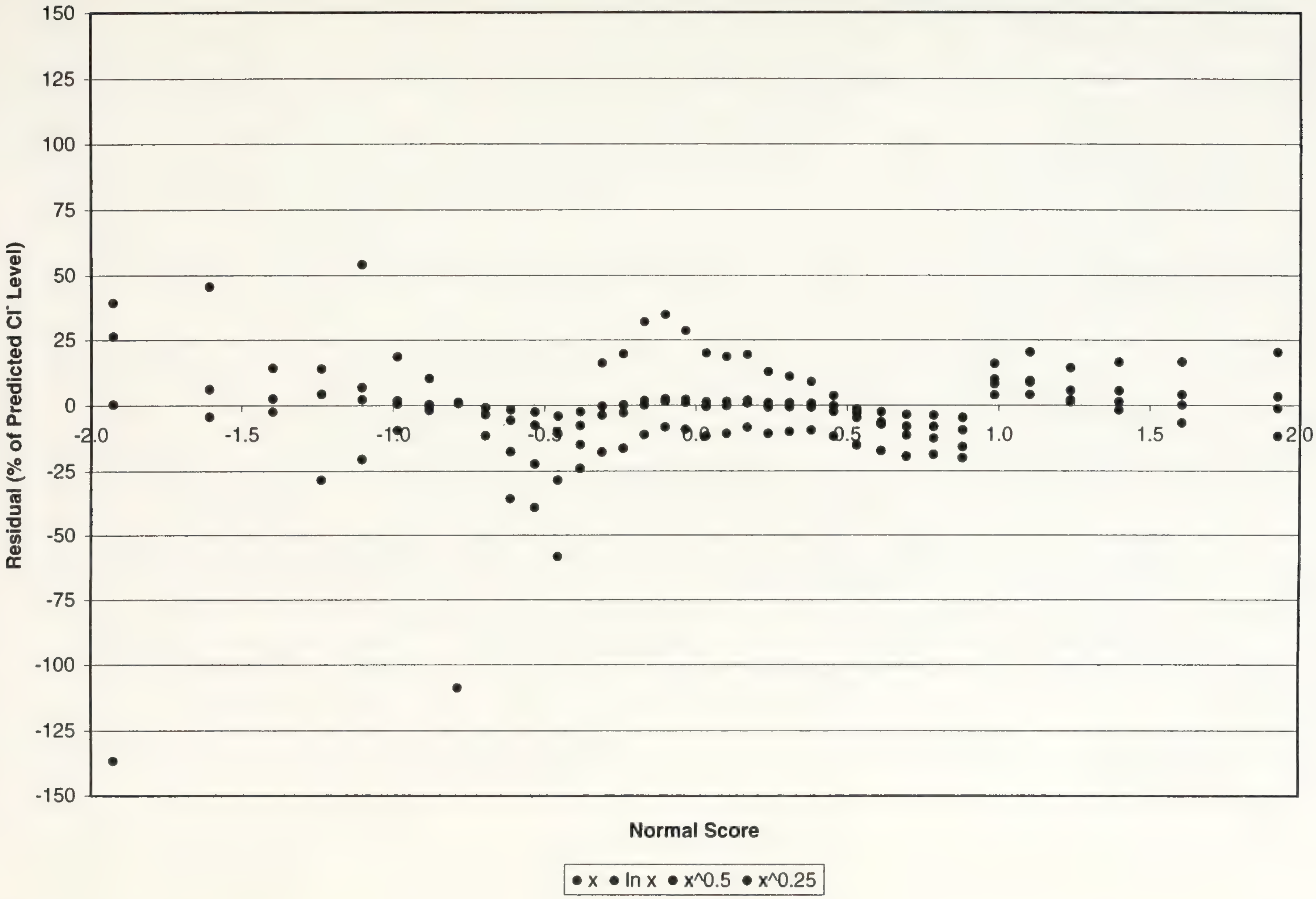


Normal Score Plot for NaCl Bridges

Reid Crowther
PROJECT NUMBER: 77054-00-3

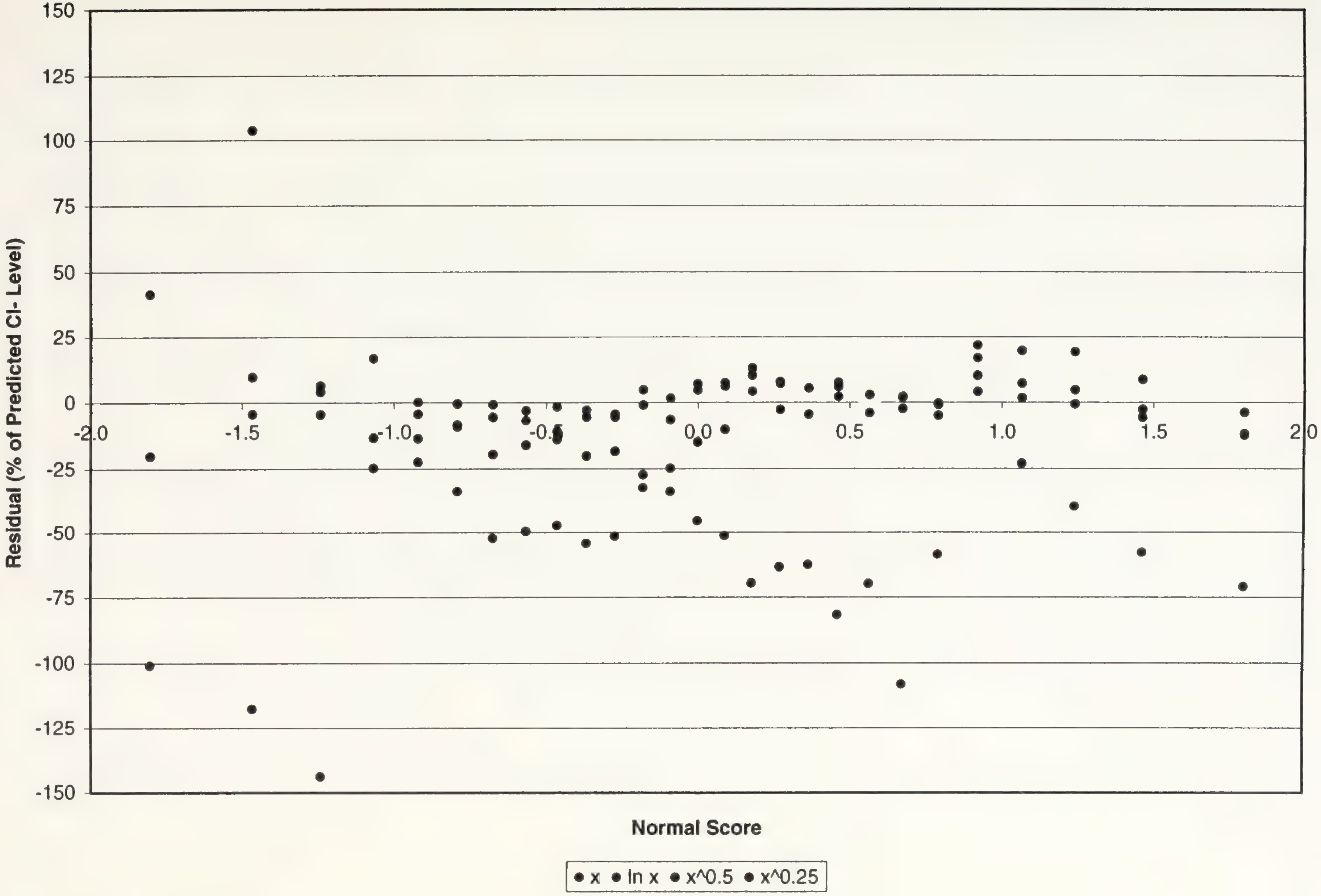


Residual Plot for $MgCl_2$ Bridges (shoulder - 0.5" depth)

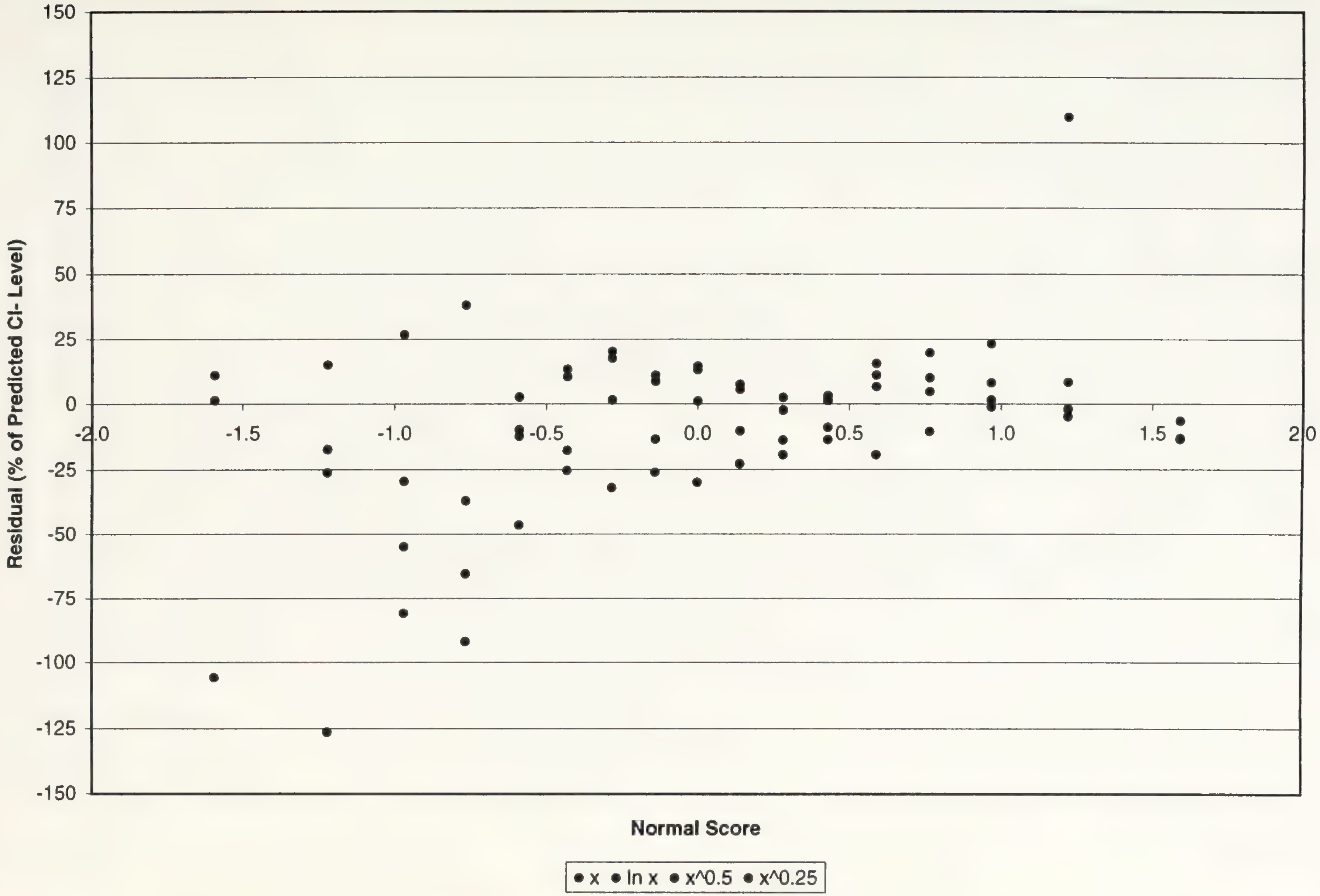


APPENDIX A-12

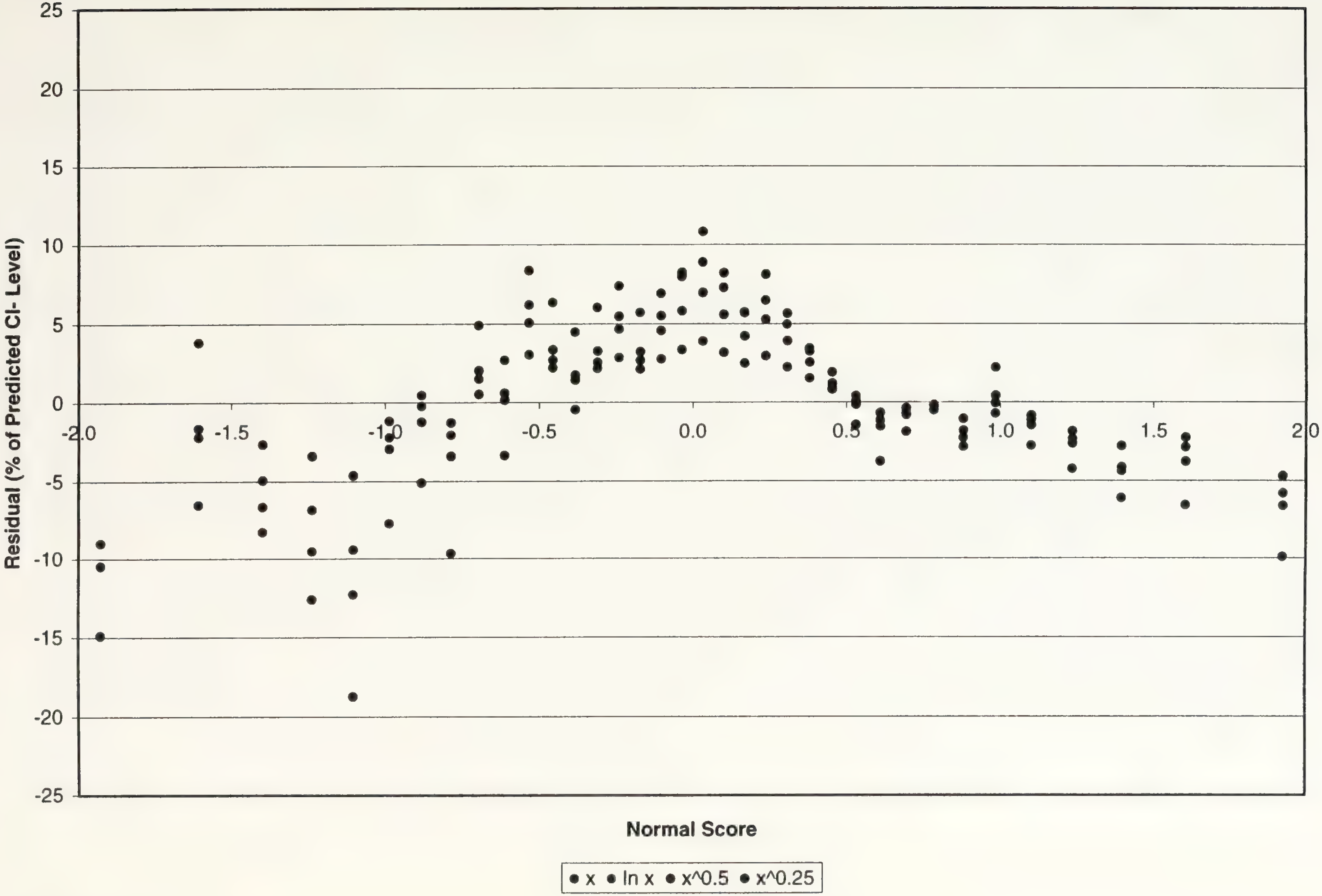
Residual Plot for MgCl$_2$ Bridges (shoulder - 1.5" depth)



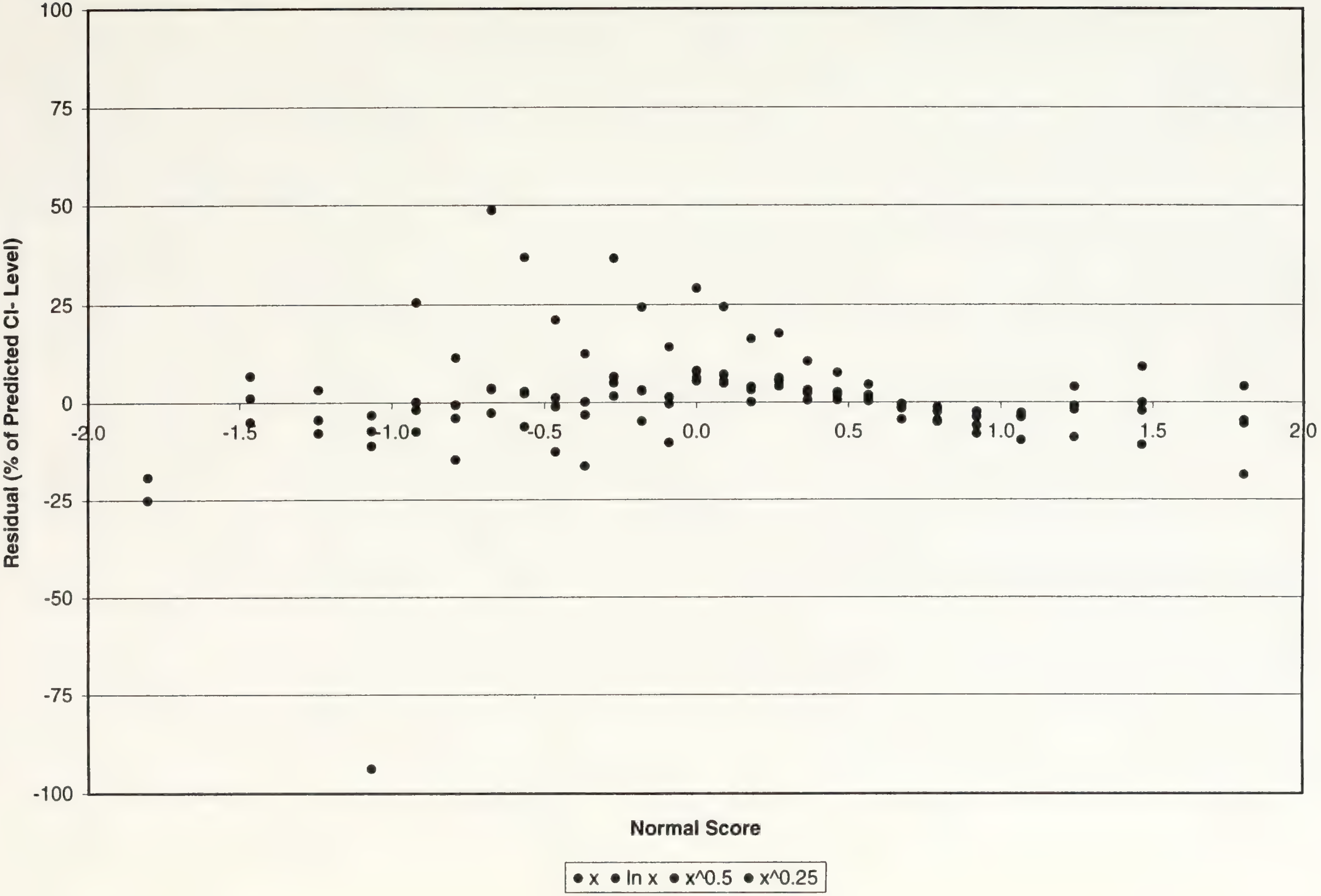
Residual Plot for $MgCl_2$ Bridges (shoulder - 2.25" depth)



Residual Plot for MgCl$_2$ Bridges (right wheel - 0.5" depth)

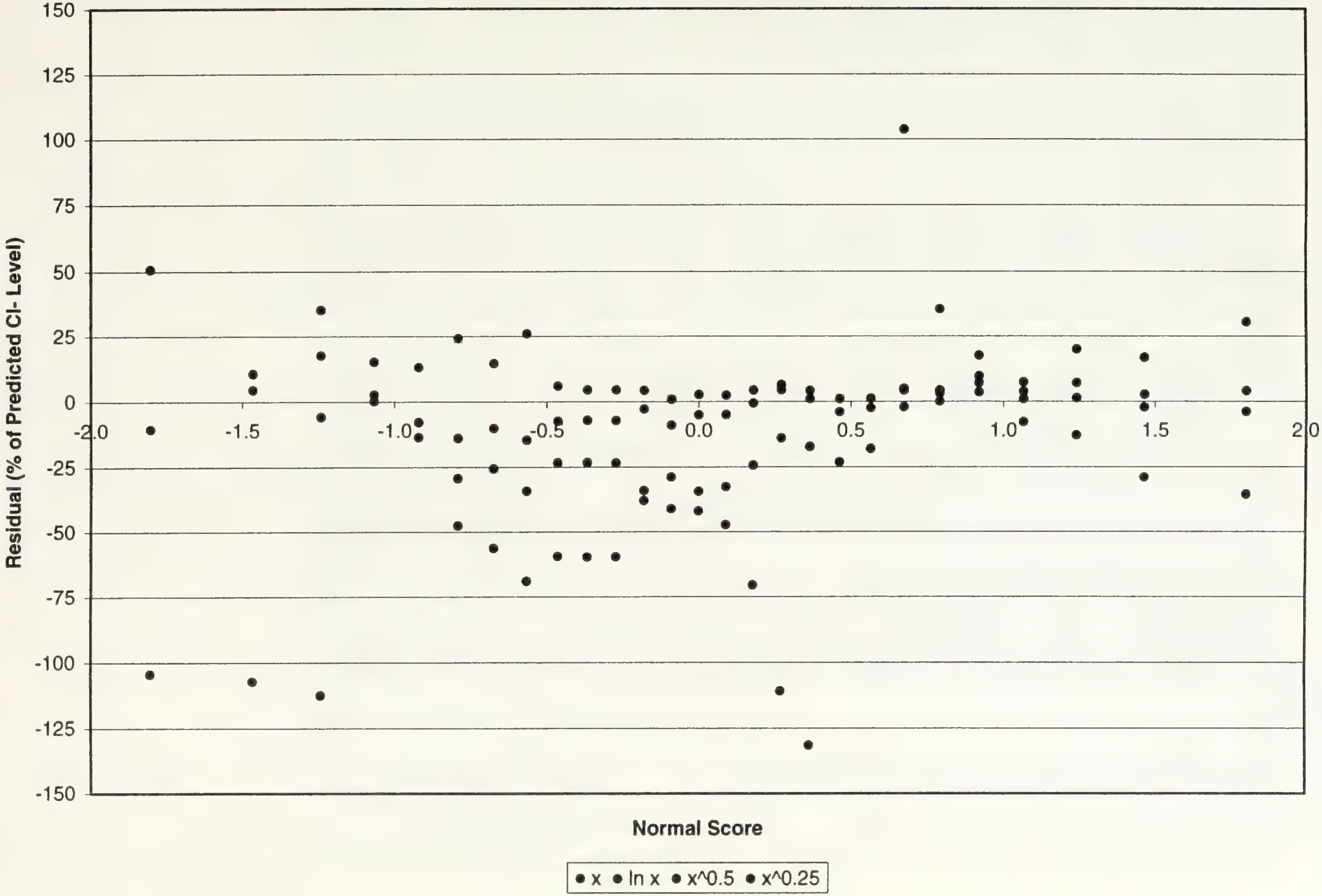


Residual Plot for $MgCl_2$ Bridges (right wheel - 1.5" depth)



Residual Plot for $MgCl_2$ Bridges (right wheel - 2.25" depth)

PROJECT NUMBER: 77054-00-3



$X^{1/4}$-Transformed Chloride Data for $MgCl_2$ Treated Bridges

Bridge No.	Cl^- Readings Along Shoulder (lb/yd^3)			Cl^- Readings Along Right Wheel (lb/yd^3)		
	0.5" Test Depth	1.5" Test Depth	2.25" Test Depth	0.5" Test Depth	1.5" Test Depth	2.25" Test Depth
01+ 09821	1.48	1.11	0.77	1.71	1.45	1.15
	0.96	1.09	0.58	1.79	1.48	0.96
	1.51	0.58		1.67	1.51	1.12
	1.05			1.69		
05 + 01481	1.53	0.94	0.66	1.69	1.19	0.44
	1.58	1.00	0.63	1.61	1.41	0.84
	1.48	1.13		1.85	1.38	0.58
	1.45			1.71		
06 + 05481	1.12	0.66	0.77	1.48	1.19	1.01
	1.23	0.44	0.44	1.37	1.07	0.53
	0.94	0.95		1.34	1.00	0.69
	1.27			1.38		
10 + 01221	0.77	0.53	0.00	1.53	1.21	0.53
	0.73	0.58	0.00	1.48	1.09	0.53
	0.87	0.79		1.19	1.17	0.44
	1.02			1.53		
10 + 07441	1.25	0.94	0.53	1.45	0.95	0.44
	1.19	0.98	0.63	1.36	0.69	0.72
	1.28	0.63		1.58	0.95	0.66
	1.21			1.71		
23 + 00631	0.93	0.44	0.00	1.75	1.38	1.02
	1.15	0.00	0.00	1.79	1.29	0.84
	0.95	0.44		1.71	1.29	0.58
	1.00			1.63		
29 + 02051	1.27	1.01	0.75	1.71	1.45	1.20
	1.29	1.13	1.12	1.84	1.61	1.30
	1.26	1.13		1.79	1.63	1.38
	1.19			1.80		
29 + 02052	1.00	0.89	0.72	1.58	1.46	1.21
	1.02	0.86	0.75	1.58	1.36	0.91
	1.01	0.98		1.65	1.29	0.89
	1.09			1.63		
29 + 03682	1.27	0.66	0.63	1.73	1.43	1.05
	1.30	0.79	0.58	1.75	1.56	1.27
	1.17	0.69		1.71	1.41	1.02
	1.23			1.69		

$X^{1/4}$-Transformed Chloride Data for NaCl Treated Bridges

Bridge No.	Cl^- Readings Along Shoulder (lb/yd^3)			Cl^- Readings Along Right Wheel (lb/yd^3)		
	0.5" Test Depth	1.5" Test Depth	2.25" Test Depth	0.5" Test Depth	1.5" Test Depth	2.25" Test Depth
34 + 02081	1.05	0.98	0.91	1.58	1.21	0.86
	1.14	0.00	0.00	1.51	0.98	0.44
	0.84	0.81		1.48	1.02	0.53
	1.09			1.61		
34 + 02082	1.16	0.53	0.00	1.56	1.12	0.69
	0.87	0.86	0.44	1.65	1.19	0.53
	1.03	0.90		1.56	1.31	0.53
	1.03			1.73		
39 + 08052	1.23	0.91	0.53	1.63	1.30	0.53
	1.40	0.90	0.00	1.61	1.38	0.86
	1.35	0.87		1.45	0.75	0.53
	1.30			1.38		
39 + 09911	1.27	1.17	1.15	1.65	1.37	1.11
	1.17	1.06	0.79	1.82	1.38	1.16
	1.17	0.94		1.63	1.33	1.17
	1.14			1.77		
39 + 09912	1.29	0.66	0.00	1.61	0.83	0.53
	1.29	0.79	0.53	1.35	0.96	0.00
	1.25	0.53		1.61	1.08	0.00
	1.08			1.53		
42 + 09191	1.17	0.81	0.44	1.53	1.16	0.53
	1.07	0.00	0.00	1.73	1.37	0.66
	1.36	0.91		1.65	1.02	0.53
	1.14			1.58		
58 + 05501	1.18	0.86	0.53	1.61	1.20	0.53
	0.78	0.83	0.89	1.69	1.32	0.63
	1.18	0.84		1.73	1.02	0.69
	1.05			1.56		
58 + 05502	1.09	0.72	0.58	1.12	0.53	0.44
	1.19	1.03	0.00	1.41	0.87	0.58
	1.28	0.58		1.17	0.00	0.00
	1.05			1.48		

$X^{1/4}$-Transformed Chloride Data for Rehabilitated Bridges

Bridge No.	Cl$^-$ Readings Along Shoulder (lb/yd³) 0.5" Test Depth	1.5" Test Depth	2.25" Test Depth	Cl$^-$ Readings Along Right Wheel (lb/yd³) 0.5" Test Depth	1.5" Test Depth	2.25" Test Depth
45 + 01802	0.83	0.00	0.00	1.05	0.00	0.00
(epoxy site)	0.89	0.69	0.00	0.99	0.00	0.00
	1.00	0.96		1.48	0.91	0.00
	1.09			1.31		
53 + 07232	1.09	0.44	1.00	1.51	1.07	1.28
(latex site)	1.15	0.63	0.87	1.28	0.58	1.04
	1.36	0.00		1.41	0.89	1.18
	1.14			1.37		
57 + 04722	0.99	0.72	0.00	1.61	1.41	1.04
(epoxy site)	1.38	0.94	0.81	1.58	1.53	1.32
	1.30	1.19		1.41	1.08	0.90
	1.35			1.19		

Descriptive Measures for $X^{1/4}$ Transformed Chloride Data (by bridge type)

	Cl^- Readings Along Shoulder			Cl^- Readings Along Right Wheel		
	0.5" Test Depth	1.5" Test Depth	2.25" Test Depth	0.5" Test Depth	1.5" Test Depth	2.25" Test Depth
$MgCl_2$ Bridges						
No. of data points (n)	36	27	18	36	27	27
Mean (μ)	1.17	0.79	0.53	1.63	1.29	0.86
Standard Deviation (σ)	0.21	0.28	0.32	0.16	0.23	0.29
Coeff. Of Variation (V)	0.18	0.35	0.61	0.10	0.17	0.34
NaCl Bridges						
No. of data points (n)	32	24	16	32	24	24
Mean (μ)	1.15	0.77	0.42	1.56	1.07	0.59
Standard Deviation (σ)	0.14	0.28	0.39	0.15	0.32	0.31
Coeff. Of Variation (V)	0.13	0.37	0.91	0.10	0.30	0.53
Rehab'd Bridges						
No. of data points (n)	12	9	6	12	9	9
Mean (μ)	0.45	0.25	0.18	0.54	0.33	0.30
Standard Deviation (σ)	0.07	0.17	0.20	0.08	0.22	0.23
Coeff. Of Variation (V)	0.16	0.67	1.10	0.15	0.66	0.77

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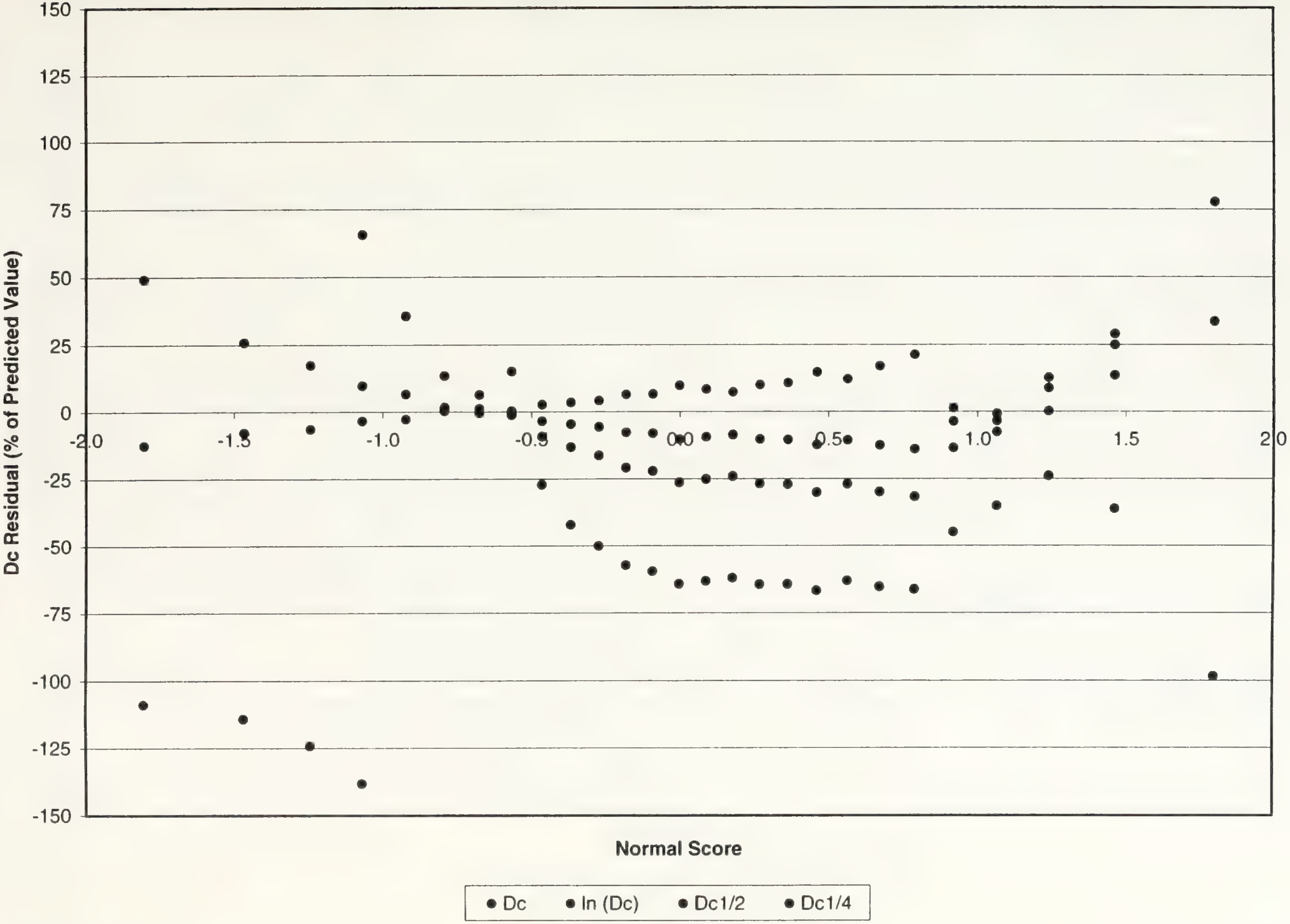
Residual Plot for $MgCl_2$ Bridge Deck Transformations (shoulder)



MgCl2 Residual (sh)
Dc Statistical Analysis.xls

APPENDIX A-15

Printed:
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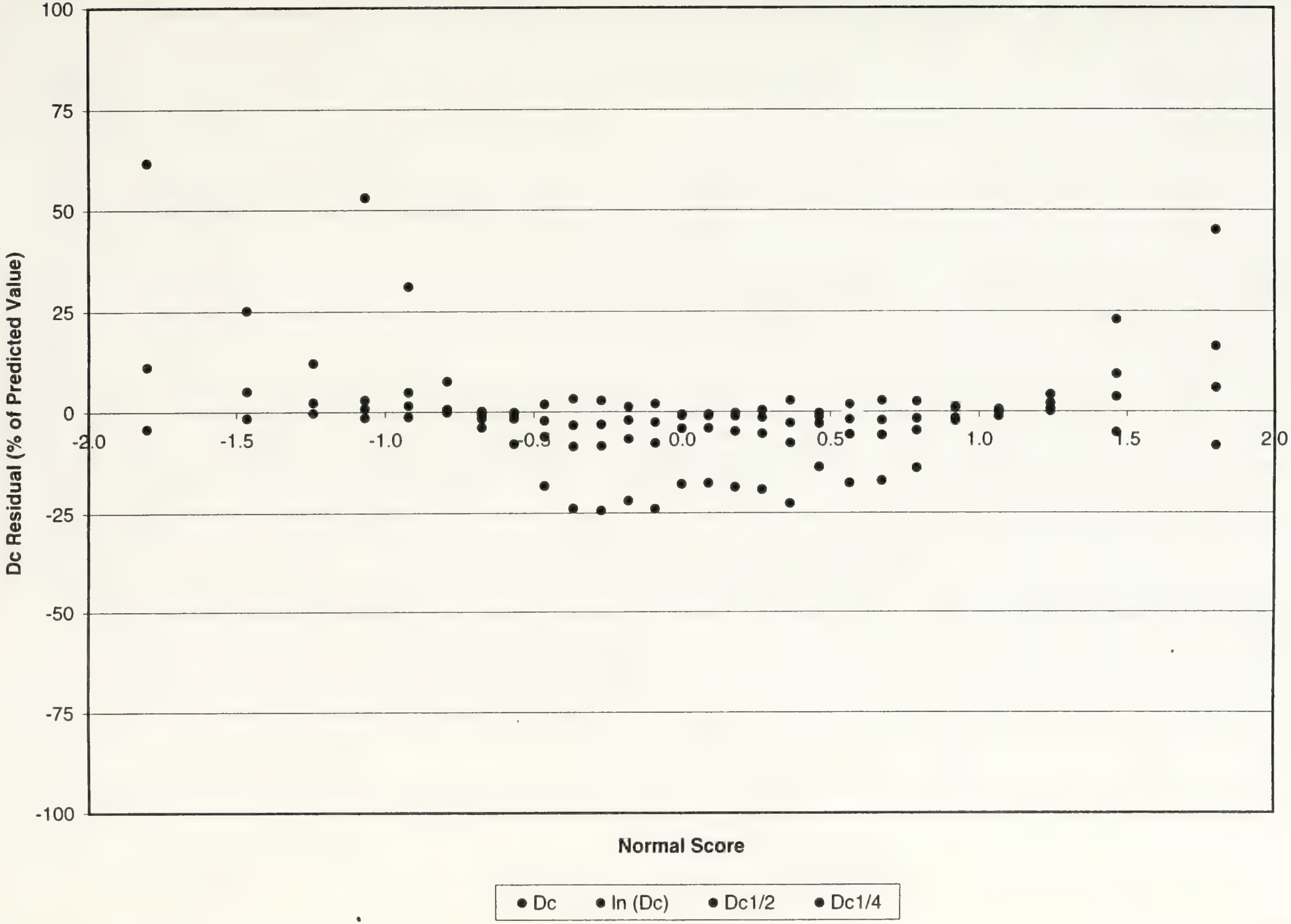
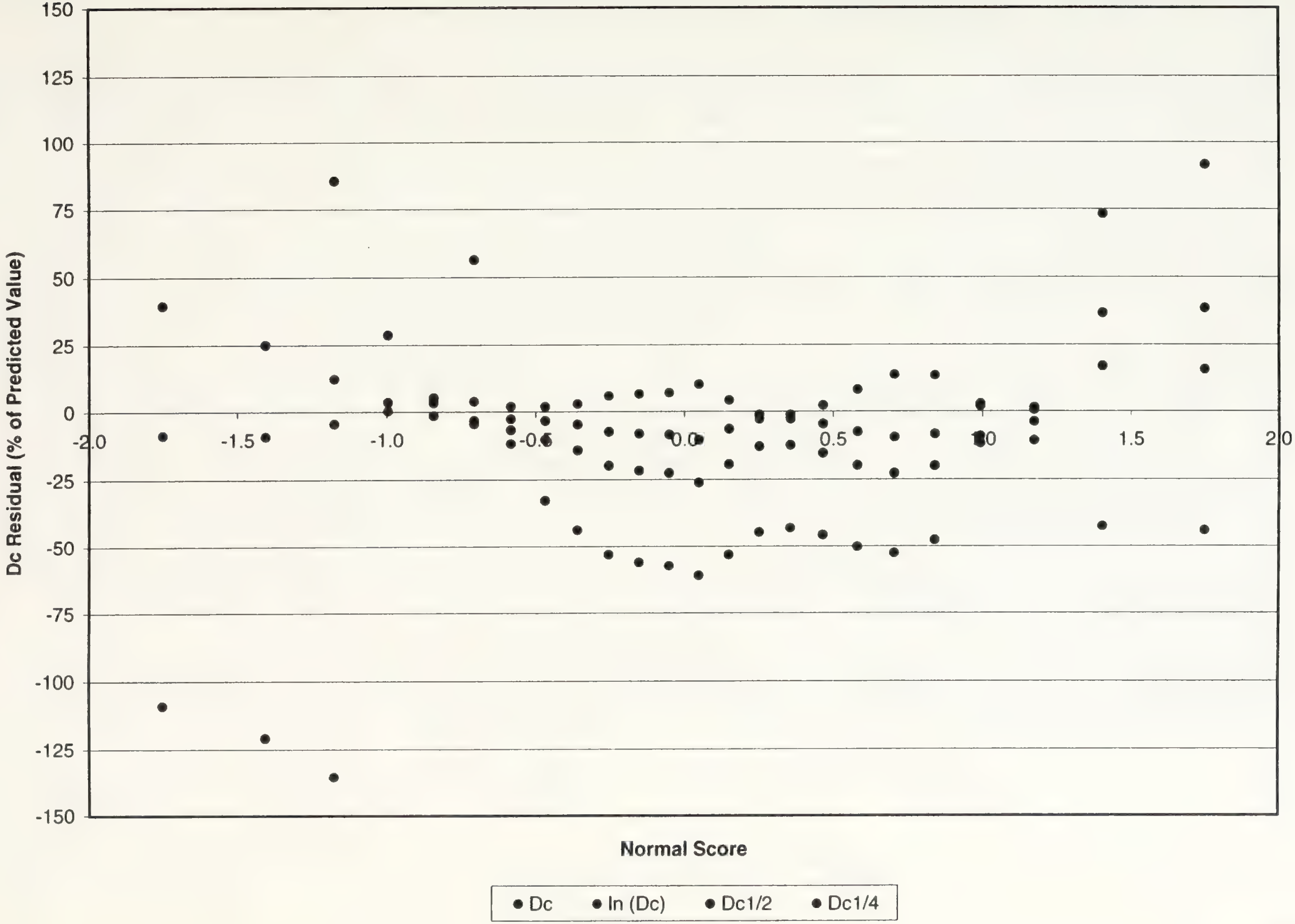
Residual Plot for MgCl$_2$ Bridge Deck Transformations (right wheel)



Residual Plot for NaCl Bridge Deck Transformations (shoulder)



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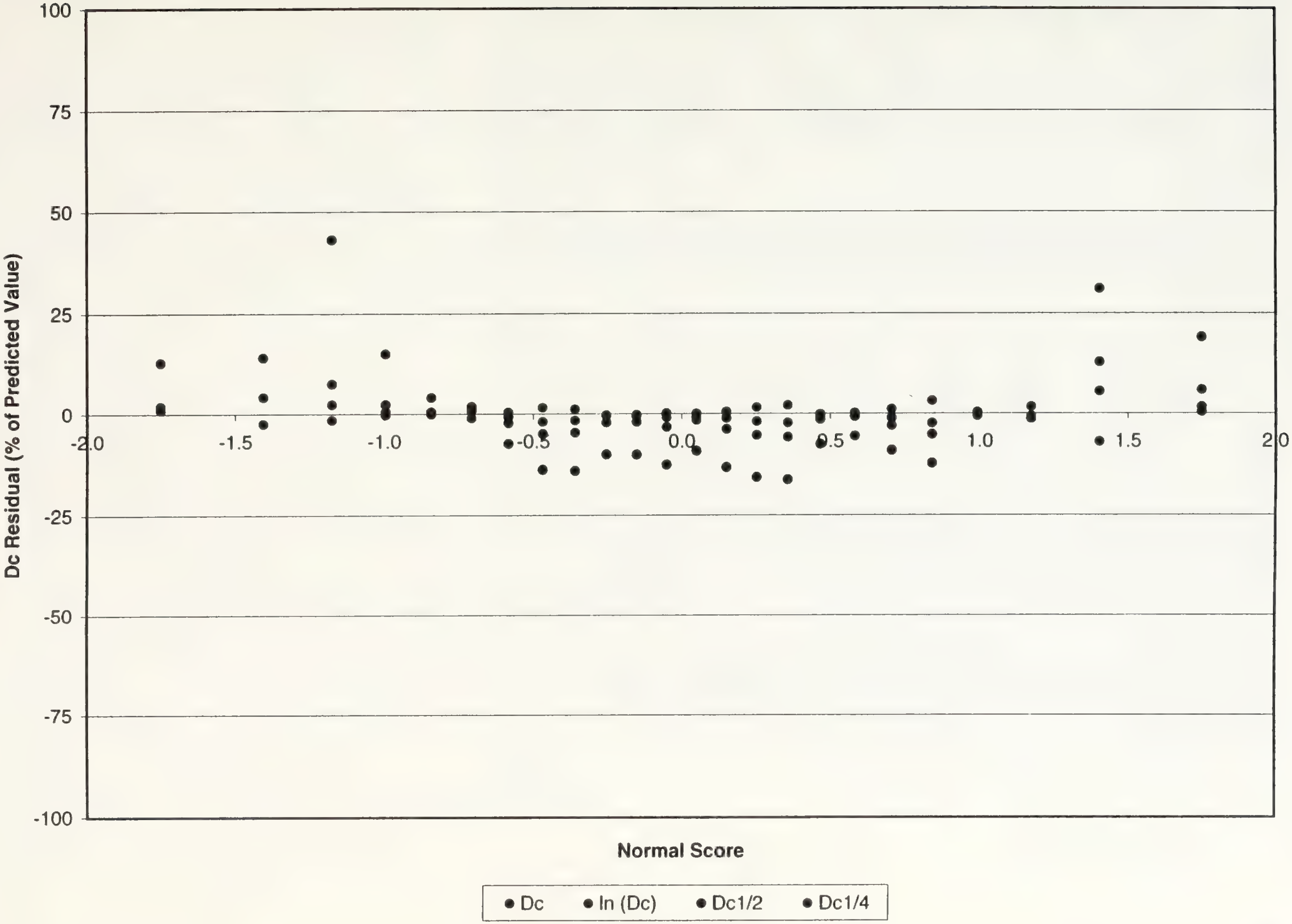
PROJECT NUMBER: 77054-00-3

Residual Plot forNaCl Bridge Deck Transformations (right wheel)



Ln-Transformed Diffusion Coefficient Summary for $MgCl_2$ and NaCl Treated Bridges

$MgCl_2$ Bridges			NaCl Bridges		
Bridge No.	Avg. D_c (ln-transformed)		Bridge No.	Avg. D_c (ln-transformed)	
	Shoulder	Right Wheel		Shoulder	Right Wheel
01+ 09821	-3.040	-2.278	34 + 02081	-0.765	-2.964
	-3.320	-1.864		-4.080	-3.717
	-3.892	-2.628		-2.911	-3.703
05 + 01481	-3.612	-3.560	34 + 02082	-4.190	-3.283
	-3.450	-2.935		-2.641	-3.260
	-2.646	-2.123		-1.645	-3.420
06 + 05481	-2.901	-2.451	39 + 08052	-3.206	-2.982
	-3.721	-3.156		-3.721	-3.833
	-2.917	-3.052		-3.352	-2.358
10 + 01221	-3.423	-3.050	39 + 09911	-0.519	-2.367
	-3.530	-2.561		-1.538	-2.725
	-2.697	-3.290		-2.256	-2.781
10 + 07441	-3.175	-3.675	39 + 09912	-4.141	-4.057
	-3.010	-3.814		-3.581	-3.603
	-4.063	-3.542		-4.148	-3.387
23 + 00631	-4.020	-2.774	42 + 09191	-3.456	-3.215
	-4.227	-3.018		-4.576	-3.681
	-4.320	-3.231		-2.441	-2.996
29 + 02051	-2.717	-2.216	58 + 05501	-3.240	-3.293
	-0.935	-1.495		-2.478	-3.485
	-0.017	-1.931		-2.519	-3.067
29 + 02052	-1.821	-1.216	58 + 05502	-3.937	-3.966
	-2.070	-2.822		-3.483	-3.915
	-1.295	-2.286		-2.477	-4.444
29 + 03682	-3.636	-2.513			
	-3.327	-2.463			
	-3.878	-1.742			

Hypothesis Testing of Cl^- Levels for $MgCl_2$ and NaCl Treated Bridges

T-TEST - *Comparison of the Data Mean*

Null Hypothesis: $\mu_{Mg} - \mu_{Na} = 0$
Alternate Hypothesis: $\mu_{Mg} - \mu_{Na} > 0$
Significance Level: $\alpha = 0.05$

		$x^{1/4}$ Transformed			$x^{1/4}$ Transformed				
Data Group	n_{MgCl2}	μ_{MgCl2}	σ_{MgCl2}	n_{NaCl}	μ_{NaCl}	σ_{NaCl}	$t_{\alpha/2}$	t	Hypothesis Test Result
0.5" Shoulder	36	1.17	0.21	32	1.15	0.14	1.997	0.456	accept null hypothesis
1.5" Shoulder	27	0.79	0.28	24	0.77	0.28	2.010	0.255	accept null hypothesis
2.25" Shoulder	18	0.53	0.32	16	0.42	0.39	2.037	0.903	accept null hypothesis
0.5" R. Wheel	36	1.63	0.16	32	1.56	0.15	1.997	1.854	accept null hypothesis
1.5" R. Wheel	27	1.29	0.23	24	1.07	0.32	2.010	2.842	reject null hypothesis
2.25" R. Wheel	27	0.86	0.29	24	0.59	0.31	2.010	3.213	reject null hypothesis

F-TEST - *Comparison of the Data Variance*

Null Hypothesis: $\sigma^2_{Mg} = \sigma^2_{Na}$
Alternate Hypothesis: $\sigma^2_{Mg} \neq \sigma^2_{Na}$
Significance Level: $\alpha = 0.05$

		$x^{1/4}$ Transformed		$x^{1/4}$ Transformed			
Test	n_{MgCl2}	σ_{MgCl2}	n_{NaCl}	σ_{NaCl}	$F_{\alpha/2}$	F	Decision
0.5" Shoulder	36	0.21	32	0.14	2.020	2.250	variances not equal
1.5" Shoulder	27	0.28	24	0.28	2.276	1.000	variances equal
2.25" Shoulder	18	0.32	16	0.39	2.813	0.673	variances equal
0.5" R. Wheel	36	0.16	32	0.15	2.020	1.138	variances equal
1.5" R. Wheel	27	0.23	24	0.32	2.276	0.517	variances equal
2.25" R. Wheel	27	0.29	24	0.31	2.276	0.875	variances equal

CONFIDENCE INTERVALS - *The Difference Range of the Means*

Confidence Interval: 95% ($\alpha = \pm 2.5\%$)

Data Group	Difference Between the Means (lb/yd^3)
0.5" Shoulder	n/a (no difference between μ)
1.5" Shoulder	n/a (no difference between μ)
2.25" Shoulder	n/a (no difference between μ)
0.5" R. Wheel	n/a (no difference between μ)
1.5" R. Wheel	$0.56 < \mu_{Mg}-\mu_{Na} < 2.28$
2.25" R. Wheel	$0.16 < \mu_{Mg}-\mu_{Na} < 1.06$

Hypothesis Testing of Difusion Coefficients for $MgCl_2$ and NaCl Treated Bridges

T-TEST - *Comparison of the Data Mean*

Null Hypothesis: $\mu_{Mg} - \mu_{Na} = 0$
Alternate Hypothesis: $\mu_{Mg} - \mu_{Na} > 0$
Significance Level: $\alpha = 0.05$

		Ln Transformed			Ln Transformed				
Test	n_{MgCl2}	μ_{MgCl2}	σ_{MgCl2}	n_{NaCl}	μ_{NaCl}	σ_{NaCl}	$t_{\alpha/2}$	t	Hypothesis Test Result
Shoulder	27	-3.025	1.034	24	-2.971	1.083	2.010	-0.182	accept null hypothesis
Right Wheel	27	-2.655	0.674	24	-3.354	0.522	2.010	4.102	reject null hypothesis

F-TEST - *Comparison of the Data Variance*

Null Hypothesis: $\sigma^2_{Mg} = \sigma^2_{Na}$
Alternate Hypothesis: $\sigma^2_{Mg} \neq \sigma^2_{Na}$
Significance Level: $\alpha = 0.05$

		Ln Transformed		Ln Transformed			
Test	n_{MgCl2}	σ_{MgCl2}	n_{NaCl}	σ_{NaCl}	$F_{\alpha/2}$	F	Decision
Shoulder	27	1.034	24	1.083	2.276	0.912	variances equal
Right Wheel	27	0.674	24	0.522	2.276	1.667	variances equal

CONFIDENCE INTERVALS - *The Difference Range of the Means*

Confidence Interval: 95% ($\alpha = \pm 2.5\%$)

Data Group	Difference Between the Means (in^2/yr)
Shoulder Right Wheel	0.024 $< \mu_{Mg} - \mu_{Na} <$ 0.072

APPENDIX B

MONTANA BRIDGE INVENTORY AND INVENTORY ANALYSIS

Samples of Montana Bridge Inventory - All Bridges

	Bridge No.	Route No.	Type Structure	Deck Wearing Surface	Deck Memb Type	Spans	MaxSpan(m)	Length (m)	Deck Wdth (m)	Deck Area	Year Built	Year Rehab'd	ADT
Category 1	I00090061+0793	00090	Prestressed Concrete Stringer/Gi	5 Epoxy Overlay	0 None	3	14.02	39.624	12.405	459	1959	0	6,720
	I00090061+0793	00090	Prestressed Concrete Stringer/Gi	5 Epoxy Overlay	0 None	3	14.02	39.624	12.405	492	1959	0	6,720
	I00090065+0497	00090	Prestressed Concrete Stringer/Gi	5 Epoxy Overlay	3 Epoxy	4	40.538	136.55	13.411	1582	1981	0	6,720
	I00090065+0497	00090	Steel Continuous Stringer/Girder	5 Epoxy Overlay	0 None	8	17.068	135.94	9.509	1160	1965	0	6,720
	I00090066+0279	00090	Steel Continuous Stringer/Girder	1 Monolithic Concrete	3 Epoxy	5	57.912	264.261	13.533	3335	1981	0	6,720
	I00090066+0279	00090	Steel Continuous Girder-Floorbea	5 Epoxy Overlay	0 None	7	64.008	245.973	9.601	2099	1965	0	6,720
	I00090066+0421	00090	Prestressed Concrete Stringer/Gi	1 Monolithic Concrete	3 Epoxy	4	32.918	100.279	13.533	1265	1981	0	6,720
	I00090066+0421	00090	Steel Stringer/Girder	5 Epoxy Overlay	0 None	7	15.544	103.327	9.692	882	1965	0	6,720
	I00090069+0041	00090	Prestressed Concrete Stringer/Gi	1 Monolithic Concrete	3 Epoxy	4	17.373	60.96	12.618	706	1981	0	6,720
	I00090069+0041	00090	Prestressed Concrete Stringer/Gi	1 Monolithic Concrete	3 Epoxy	4	18.897	57.912	14.264	777	1964	0	6,720
	I00090187+0689	00090	Prestressed Concrete Stringer/Gi	1 Monolithic Concrete	0 None	3	15.544	46.634	9.601	398	1961	0	6,580
	I00090187+0689	00090	Prestressed Concrete Stringer/Gi	1 Monolithic Concrete	0 None	3	15.544	46.634	9.631	398	1961	0	6,580
	I00090191+0864	00090	Concrete Continuous Slab	1 Monolithic Concrete	0 None	3	9.144	24.384	13.502	309	1975	0	6,580
Category 2	P00008088+005	00287	Steel Continuous Stringer/Girder	1 Monolithic Concrete	0 None	7	23.469	117.652	9.753	1004	1955	0	3,040
	P00008088+029	00287	Steel Continuous Stringer/Girder	1 Monolithic Concrete	0 None	8	38.1	210.312	9.662	1795	1955	0	3,040
	P00057062+053	00087	Prestressed Concrete Stringer/Gi	1 Monolithic Concrete	0 None	3	20.421	54.559	14.02	723	1971	0	3,020
	P00057079+065	00087	Concrete Tee Beam	6 Bituminous	0 None	5	12.192	50.292	7.62	368	1936	0	3,020
	P00001027+087	00002	Prestressed Concrete Stringer/Gi	1 Monolithic Concrete	0 None	1	15.24	15.849	12.588	190	1989	0	3,010
	P00048001+006	00047	Prestressed Concrete Stringer/Gi	1 Monolithic Concrete	0 None	4	29.26	86.868	14.112	1152	1970	0	3,010
	S00486001+040	00486	Steel Continuous Stringer/Girder	1 Monolithic Concrete	0 None	4	33.528	122.834	16.855	1778	1972	0	2,970
	P00001404+057	00002	Concrete Tee Beam	6 Bituminous	0 None	3	10.972	28.651	9.753	245	1942	0	2,950
	P00078034+091	00078	Wood or Timber Stringer/Girder	6 Bituminous	0 None	2	7.62	15.849	7.924	117	1943	0	2,940
	P00078039+060	00078	Steel Stringer/Girder	6 Bituminous	0 None	1	5.181	5.486	7.65	40	1943	0	2,940
	P00078042+003	00078	Wood or Timber Stringer/Girder	6 Bituminous	0 None	1	5.791	6.4	7.924	48	1935	0	2,940
	P00078043+050	00078	Wood or Timber Stringer/Girder	6 Bituminous	0 None	1	5.791	6.4	8.016	47	1935	0	2,940
	P00078043+059	00078	Wood or Timber Stringer/Girder	6 Bituminous	0 None	3	7.62	19.812	7.924	147	1943	0	2,940
	P00078046+013	00078	Steel Continuous Girder-Floorbea	1 Monolithic Concrete	0 None	4	48.768	175.564	9.479	1498	1957	0	2,940
	P00001611+007	00002	Steel Continuous Stringer/Girder	1 Monolithic Concrete	0 None	5	27.432	89.611	10.515	710	1937	0	2,930
	P00016047+055	00087	Prestressed Concrete Stringer/Gi	1 Monolithic Concrete	0 None	3	28.041	83.82	12.954	1035	1996	0	2,920
Category 3	S00401002+040	00401	Concrete Slab	8 Gravel	0 None	1	2.438	3.048	9.784	29	1982	0	350
	S00408004+000	00408	Wood or Timber Stringer/Girder	6 Bituminous	0 None	3	7.62	22.86	7.924	167	1953	0	350
	P00026006+014	00023	Prestressed Concrete Stringer/Gi	1 Monolithic Concrete	0 None	1	27.432	28.041	12.832	336	1986	0	340
	P00046015+079	00043	Concrete Continuous Slab	6 Bituminous	0 None	3	6.705	18.288	9.235	156	1961	0	340
	P00046025+082	00043	Prestressed Concrete Stringer/Gi	1 Monolithic Concrete	0 None	4	17.373	65.532	9.052	559	1962	0	340
	S00244018+050	00244	Wood or Timber Stringer/Girder	6 Bituminous	0 None	4	5.791	23.164	7.924	169	1948	0	340
	S00244023+030	00244	Wood or Timber Stringer/Girder	6 Bituminous	0 None	5	7.62	38.1	7.924	279	1941	0	340
	S00451033+034	00451	Steel Continuous Stringer/Girder	6 Bituminous	0 None	4	7.924	19.812	10.424	181	1949	0	340
	S00451034+004	00451	Steel Continuous Stringer/Girder	6 Bituminous	0 None	4	7.924	19.812	10.424	181	1949	0	340
	P00027001+029	00007	Wood or Timber Stringer/Girder	6 Bituminous	0 None	2	5.791	11.582	7.924	85	1940	0	330
	P00027002+030	00007	Wood or Timber Stringer/Girder	6 Bituminous	0 None	2	5.791	11.582	7.924	85	1940	0	330
	P00027005+062	00007	Wood or Timber Stringer/Girder	6 Bituminous	0 None	3	5.791	17.373	7.924	127	1940	0	330
	P00027006+008	00007	Wood or Timber Stringer/Girder	6 Bituminous	0 None	5	5.791	28.956	7.924	212	1940	0	330

Number, Deck Area, and Replacement Cost of Bridge Inventory Sorted by ADT (Sample of Inventory)

		Category 1. Interstate Bridges			Category 2. ADT >= 500			Category 3. ADT < 500			Total - All Bridges		
ADT (Min of range)	ADT (Max of range)	Number of bridges in range	Deck area of bridges in range (m²)	Replacement cost of bridges in range ($)	Number of bridges in range	Deck area of bridges in range (m²)	Replacement cost of bridges in range ($)	Number of bridges in range	Deck area of bridges in range (m²)	Replacement cost of bridges in range ($)	Total number of bridges in range	Total deck area of bridges in range (m²)	Total replacement cost of bridges in range ($)
0	99	0	0	0	0	0	0	62	13,115	13,115,000	62	13,115	13,115,000
100	199	0	0	0	0	0	0	2,229	380,135	380,135,000	2,229	380,135	380,135,000
200	299	0	0	0	0	0	0	162	35,836	35,836,000	162	35,836	35,836,000
300	399	0	0	0	0	0	0	179	40,480	40,480,000	179	40,480	40,480,000
400	499	0	0	0	0	0	0	118	28,231	28,231,000	118	28,231	28,231,000
500	599	0	0	0	97	26,002	26,002,000	0	0	0	97	26,002	26,002,000
600	699	0	0	0	64	15,379	15,379,000	0	0	0	64	15,379	15,379,000
700	799	0	0	0	67	29,975	29,975,000	0	0	0	67	29,975	29,975,000
800	899	0	0	0	44	11,665	11,665,000	0	0	0	44	11,665	11,665,000
900	999	0	0	0	69	21,859	21,859,000	0	0	0	69	21,859	21,859,000
1000	1099	0	0	0	56	17,510	17,510,000	0	0	0	56	17,510	17,510,000
1100	1199	0	0	0	28	9,983	9,983,000	0	0	0	28	9,983	9,983,000
1200	1299	0	0	0	35	12,312	12,312,000	0	0	0	35	12,312	12,312,000
1300	1399	0	0	0	27	11,582	11,582,000	0	0	0	27	11,582	11,582,000
1400	1499	0	0	0	45	14,555	14,555,000	0	0	0	45	14,555	14,555,000
1500	1599	0	0	0	23	5,954	5,954,000	0	0	0	23	5,954	5,954,000
1600	1699	0	0	0	24	3,991	3,991,000	0	0	0	24	3,991	3,991,000
1700	1799	0	0	0	62	22,346	22,346,000	0	0	0	62	22,346	22,346,000
1800	1899	8	4,778	4,778,000	21	14,270	14,270,000	0	0	0	29	19,048	19,048,000
1900	1999	0	0	0	40	16,425	16,425,000	0	0	0	40	16,425	16,425,000
2000	2099	2	2,710	2,710,000	30	9,171	9,171,000	0	0	0	32	11,881	11,881,000
2100	2199	2	559	559,000	8	4,011	4,011,000	0	0	0	10	4,570	4,570,000
2200	2299	0	0	0	14	2,187	2,187,000	0	0	0	14	2,187	2,187,000
2300	2399	0	0	0	23	8,661	8,661,000	0	0	0	23	8,661	8,661,000
2400	2499	18	8,063	8,063,000	23	8,643	8,643,000	0	0	0	41	16,706	16,706,000
2500	2599	51	26,651	26,651,000	16	7,370	7,370,000	0	0	0	67	34,021	34,021,000
2600	2699	40	42,831	42,831,000	10	6,189	6,189,000	0	0	0	50	49,020	49,020,000
2700	2799	4	2,120	2,120,000	9	1,623	1,623,000	0	0	0	13	3,743	3,743,000
2800	2899	11	13,606	13,606,000	4	3,139	3,139,000	0	0	0	15	16,745	16,745,000
2900	2999	14	31,586	31,586,000	11	5,706	5,706,000	0	0	0	25	37,292	37,292,000
3000	3099	32	20,246	20,246,000	13	7,638	7,638,000	0	0	0	45	27,884	27,884,000
3100	3199	15	17,449	17,449,000	7	2,604	2,604,000	0	0	0	22	20,053	20,053,000
3200	3299	16	13,698	13,698,000	8	3,032	3,032,000	0	0	0	24	16,730	16,730,000
3300	3399	2	868	868,000	11	3,492	3,492,000	0	0	0	13	4,360	4,360,000
3400	3499	18	6,338	6,338,000	2	444	444,000	0	0	0	20	6,782	6,782,000
3500	3599	33	17,062	17,062,000	3	5,159	5,159,000	0	0	0	36	22,221	22,221,000
3600	3699	18	7,733	7,733,000	5	2,036	2,036,000	0	0	0	23	9,769	9,769,000
3700	3799	35	16,133	16,133,000	5	3,964	3,964,000	0	0	0	40	20,097	20,097,000
3800	3899	10	7,911	7,911,000	9	2,978	2,978,000	0	0	0	19	10,889	10,889,000
3900	3999	27	14,681	14,681,000	7	4,023	4,023,000	0	0	0	34	18,704	18,704,000
4000	4099	6	2,044	2,044,000	5	2,214	2,214,000	0	0	0	11	4,258	4,258,000
4100	4199	0	0	0	3	1,551	1,551,000	0	0	0	3	1,551	1,551,000
4200	4299	4	2,058	2,058,000	2	1,936	1,936,000	0	0	0	6	3,994	3,994,000
4300	4399	0	0	0	7	2,209	2,209,000	0	0	0	7	2,209	2,209,000
4400	4499	0	0	0	6	1,001	1,001,000	0	0	0	6	1,001	1,001,000
4500	4599	4	1,607	1,607,000	6	3,487	3,487,000	0	0	0	10	5,094	5,094,000
4600	4699	2	302	302,000	4	1,039	1,039,000	0	0	0	6	1,341	1,341,000
4700	4799	2	1,047	1,047,000	0	0	0	0	0	0	2	1,047	1,047,000
4800	4899	0	0	0	3	158	158,000	0	0	0	3	158	158,000
4900	4999	8	4,044	4,044,000	4	1,867	1,867,000	0	0	0	12	5,911	5,911,000
5000	5099	0	0	0	0	0	0	0	0	0	0	0	0
5100	5199	4	2,379	2,379,000	2	531	531,000	0	0	0	6	2,910	2,910,000
5200	5299	24	30,075	30,075,000	0	0	0	0	0	0	24	30,075	30,075,000
5300	5399	0	0	0	2	1,018	1,018,000	0	0	0	2	1,018	1,018,000
5400	5499	0	0	0	7	3,688	3,688,000	0	0	0	7	3,688	3,688,000
5500	5599	10	7,424	7,424,000	0	0	0	0	0	0	10	7,424	7,424,000
5600	5699	16	17,278	17,278,000	1	186	186,000	0	0	0	17	17,464	17,464,000
5700	5799	22	14,033	14,033,000	3	4,892	4,892,000	0	0	0	25	18,925	18,925,000
5800	5899	11	24,754	24,754,000	1	158	158,000	0	0	0	12	24,912	24,912,000
5900	5999	7	2,873	2,873,000	3	579	579,000	0	0	0	10	3,452	3,452,000
6000	6099	17	9,113	9,113,000	1	154	154,000	0	0	0	18	9,267	9,267,000
6100	6199	0	0	0	1	225	225,000	0	0	0	1	225	225,000
6200	6299	22	25,465	25,465,000	2	278	278,000	0	0	0	24	25,743	25,743,000
6300	6399	3	1,495	1,495,000	5	6,039	6,039,000	0	0	0	8	7,534	7,534,000
6400	6499	2	1,093	1,093,000	1	94	94,000	0	0	0	3	1,187	1,187,000
6500	6599	15	12,187	12,187,000	2	1,553	1,553,000	0	0	0	17	13,740	13,740,000
6600	6699	0	0	0	0	0	0	0	0	0	0	0	0
6700	6799	10	12,757	12,757,000	1	164	164,000	0	0	0	11	12,921	12,921,000

Number, Deck Area, and Replacement Cost of Bridges
Sorted by Year Built

		Category 1, Interstate Bridges				Category 2, ADT >= 500				Category 3, ADT < 500				Total - All Bridges		
Year Built (Min of range)	Year Built (Max of range)	Number of bridges in range	Deck area of bridges in range (m²)	Replacement cost of bridges in range ($)	Predicted Year of Replacement	Number of bridges in range	Deck area of bridges in range (m²)	Replacement cost of bridges in range ($)	Predicted Year of Replacement	Number of bridges in range	Deck area of bridges in range (m²)	Replacement cost of bridges in range ($)	Predicted Year of Replacement	Total number of bridges in range	Total deck area of bridges in range (m²)	Total replacement cost of bridges in range ($)
1880	1884	0	0	0	1930	0	0	0	0	1	178	178,000	1970	1	178	178,000
1885	1889	0	0	0	1935	0	0	0	0	0	0	0	1975	0	0	0
1890	1894	0	0	0	1940	0	0	0	0	7	1,913	1,913,000	1980	7	1,913	1,913,000
1895	1899	0	0	0	1945	0	0	0	0	8	2,184	2,184,000	1985	8	2,184	2,184,000
1900	1904	0	0	0	1950	0	0	0	0	5	1,288	1,288,000	1990	5	1,288	1,288,000
1905	1909	0	0	0	1955	1	68	68,000	1970	28	3,704	3,704,000	1995	29	3,772	3,772,000
1910	1914	0	0	0	1960	1	260	260,000	1975	66	11,350	11,350,000	2000	67	11,610	11,610,000
1915	1919	0	0	0	1965	3	182	182,000	1980	34	6,067	6,067,000	2005	37	6,249	6,249,000
1920	1924	0	0	0	1970	11	1,761	1,761,000	1985	41	6,544	6,544,000	2010	52	8,305	8,305,000
1925	1929	0	0	0	1975	16	2,408	2,408,000	1990	56	8,640	8,640,000	2015	72	11,048	11,048,000
1930	1934	0	0	0	1980	86	19,253	19,253,000	1995	225	33,847	33,847,000	2020	311	53,100	53,100,000
1935	1939	0	0	0	1985	150	35,555	35,555,000	2000	247	35,944	35,944,000	2025	397	71,499	71,499,000
1940	1944	0	0	0	1990	93	21,828	21,828,000	2005	137	19,038	19,038,000	2030	230	40,866	40,866,000
1945	1949	2	834	834,000	1995	74	15,855	15,855,000	2010	106	23,483	23,483,000	2035	182	40,172	40,172,000
1950	1954	1	433	433,000	2000	57	21,897	21,897,000	2015	182	19,906	19,906,000	2040	240	42,236	42,236,000
1955	1959	37	14,331	14,331,000	2005	118	58,124	58,124,000	2020	122	20,815	20,815,000	2045	277	93,270	93,270,000
1960	1964	159	110,119	110,119,000	2010	91	52,746	52,746,000	2025	268	44,425	44,425,000	2050	518	207,290	207,290,000
1965	1969	192	152,934	152,934,000	2015	88	62,736	62,736,000	2030	165	45,875	45,875,000	2055	445	261,545	261,545,000
1970	1974	192	131,896	131,896,000	2020	73	53,059	53,059,000	2035	222	61,072	61,072,000	2060	487	246,027	246,027,000
1975	1979	113	89,155	89,155,000	2025	35	24,924	24,924,000	2040	240	48,447	48,447,000	2065	388	162,526	162,526,000
1980	1984	102	96,394	96,394,000	2030	63	47,029	47,029,000	2045	211	36,237	36,237,000	2070	376	179,660	179,660,000
1985	1989	43	20,291	20,291,000	2035	58	22,199	22,199,000	2050	194	29,874	29,874,000	2075	295	72,364	72,364,000
1990	1994	2	992	992,000	2040	60	33,166	33,166,000	2055	130	24,179	24,179,000	2080	192	58,337	58,337,000
1995	1999	0	0	0	2045	27	23,308	23,308,000	2060	55	12,787	12,787,000	2085	82	36,095	36,095,000
	Totals	843	617,379	617,379,000		1,105	496,358	496,358,000		2,750	497,797	497,797,000		4,698	1,611,534	1,611,534,000

Number, Deck Area, and Replacement Cost of Bridges
Sorted by Replacement Year (NaCl Only)

		Category 1, Interstate Bridges			Category 2, ADT >= 500			Total - Category 1 & 2 Bridges		
$MgCl_2$ Repl Year (Min of range)	$MgCl_2$ Repl Year (Max of range)	Number of bridges in range	Deck area of bridges in range (m^2)	Replacement cost of bridges in range ($)	Number of bridges in range	Deck area of bridges in range (m^2)	Replacement cost of bridges in range ($)	Total number of bridges in range	Total deck area of bridges in range (m^2)	Total replacement cost of bridges in range ($)
1970	1974	0	0	0	1	68	78,200	1	68	78,200
1975	1979	0	0	0	1	260	299,000	1	260	299,000
1980	1984	0	0	0	3	182	209,300	3	182	209,300
1985	1989	0	0	0	11	1,761	2,025,150	11	1,761	2,025,150
1990	1994	0	0	0	16	2,408	2,769,200	16	2,408	2,769,200
1995	1999	2	834	959,100	86	19,253	22,140,950	88	20,087	23,100,050
2000	2004	1	433	497,950	150	35,555	40,888,250	151	35,988	41,386,200
2005	2009	37	14,331	16,480,650	93	21,828	25,102,200	130	36,159	41,582,850
2010	2014	159	110,119	126,636,850	74	15,855	18,233,250	233	125,974	144,870,100
2015	2019	192	152,934	175,874,100	57	21,897	25,181,550	249	174,831	201,055,650
2020	2024	192	131,896	151,680,400	118	58,124	66,842,600	310	190,020	218,523,000
2025	2029	113	89,155	102,528,250	91	52,746	60,657,900	204	141,901	163,186,150
2030	2034	102	96,394	110,853,100	88	62,736	72,146,400	190	159,130	182,999,500
2035	2039	43	20,291	23,334,650	74	53,127	61,096,050	117	73,418	84,430,700
2040	2044	2	992	1,140,800	36	25,184	28,961,600	38	26,176	30,102,400
2045	2049	2	834	959,100	66	47,211	54,292,650	68	48,045	55,251,750
2050	2054	1	433	497,950	69	23,960	27,554,000	70	24,393	28,051,950
2055	2059	37	14,331	16,480,650	76	35,574	40,910,100	113	49,905	57,390,750
2060	2064	159	110,119	126,636,850	113	42,561	48,945,150	272	152,680	175,582,000
2065	2069	192	152,934	175,874,100	150	35,555	40,888,250	342	188,489	216,762,350
2070	2074	192	131,896	151,680,400	93	21,828	25,102,200	285	153,724	176,782,600
2075	2079	113	89,155	102,528,250	74	15,855	18,233,250	187	105,010	120,761,500
2080	2084	102	96,394	110,853,100	57	21,897	25,181,550	159	118,291	136,034,650
2085	2089	43	20,291	23,334,650	118	58,124	66,842,600	161	78,415	90,177,250
	Total	1,684	1,233,766	1,418,830,900	1,715	673,549	774,581,350	3,399	1,907,315	2,193,412,250

Number, Deck Area, and Replacement Cost of Bridges
Sorted by Replacement Year (NaCl and MgCl2)

		Category 1, Interstate Bridges			Category 2, ADT >= 500			Total - Category 1 & 2 Bridges		
MgCl Repl Year (Min of range)	MgCl Repl Year (Max of range)	Number of bridges in range	Deck area of bridges in range (m²)	Replacement cost of bridges in range ($)	Number of bridges in range	Deck area of bridges in range (m²)	Replacement cost of bridges in range ($)	Total number of bridges in range	Total deck area of bridges in range (m²)	Total replacement cost of bridges in range ($)
2000	2004	9	2,848	3,275,200	308	66,764	76,778,600	317	69,612	80,053,800
2005	2009	75	41,623	47,866,450	72	16,860	19,389,000	147	58,483	67,255,450
2010	2014	269	204,457	235,125,550	101	30,084	34,596,600	370	234,541	269,722,150
2015	2019	230	161,619	185,861,850	129	63,483	73,005,450	359	225,102	258,867,300
2020	2024	150	113,925	131,013,750	102	58,314	67,061,100	252	172,239	198,074,850
2025	2029	94	87,102	100,167,300	102	70,965	81,609,750	196	158,067	181,777,050
2030	2034	14	4,813	5,534,950	77	60,061	69,070,150	91	64,874	74,605,100
2035	2039	2	992	1,140,800	69	51,154	58,827,100	71	52,146	59,967,900
2040	2044	9	2,848	3,275,200	74	25,483	29,305,450	83	28,331	32,580,650
2045	2049	75	41,623	47,866,450	61	44,306	50,951,900	136	85,929	98,818,350
2050	2054	269	204,457	235,125,550	241	63,753	73,315,950	510	268,210	308,441,500
2055	2059	230	161,619	185,861,850	130	26,446	30,412,900	360	188,065	216,274,750
2060	2064	150	113,925	131,013,750	90	19,302	22,197,300	240	133,227	153,211,050
2065	2069	94	87,102	100,167,300	78	34,954	40,197,100	172	122,056	140,364,400
2070	2074	14	4,813	5,534,950	146	85,286	98,078,900	160	90,099	103,613,850
2075	2079	2	992	1,140,800	114	71,816	82,588,400	116	72,808	83,729,200
2080	2084	0	0	0	80	58,706	67,511,900	80	58,706	67,511,900
2085	2089	0	0	0	47	39,392	45,300,800	47	39,392	45,300,800
2090	2094	0	0	0	93	45,950	52,842,500	93	45,950	52,842,500
2095	2099	0	0	0	69	36,329	41,778,350	69	36,329	41,778,350
2100	2104	0	0	0	27	23,308	26,804,200	27	23,308	26,804,200
2105	2109	0	0	0	0	0	0	0	0	0
2110	2114	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0
	Totals	1,686	1,234,758	1,419,971,700	2,210	992,716	1,141,623,400	3,896	2,227,474	2,561,595,100

With MgCl2 (20% reduction in life), 2 Generations of Bridges

APPENDIX C
ECONOMIC ANALYSIS

Present Worth Analysis:
Future Replacement Needs of all Currently Treated Bridges
($MgCl_2$ decreases remaining life by 20%)

Assumptions:

4% = Value of Money (difference between bank interest rate and inflation rate)
2000 = Current Year (for analysis purposes)
20 = Analysis Period (years)

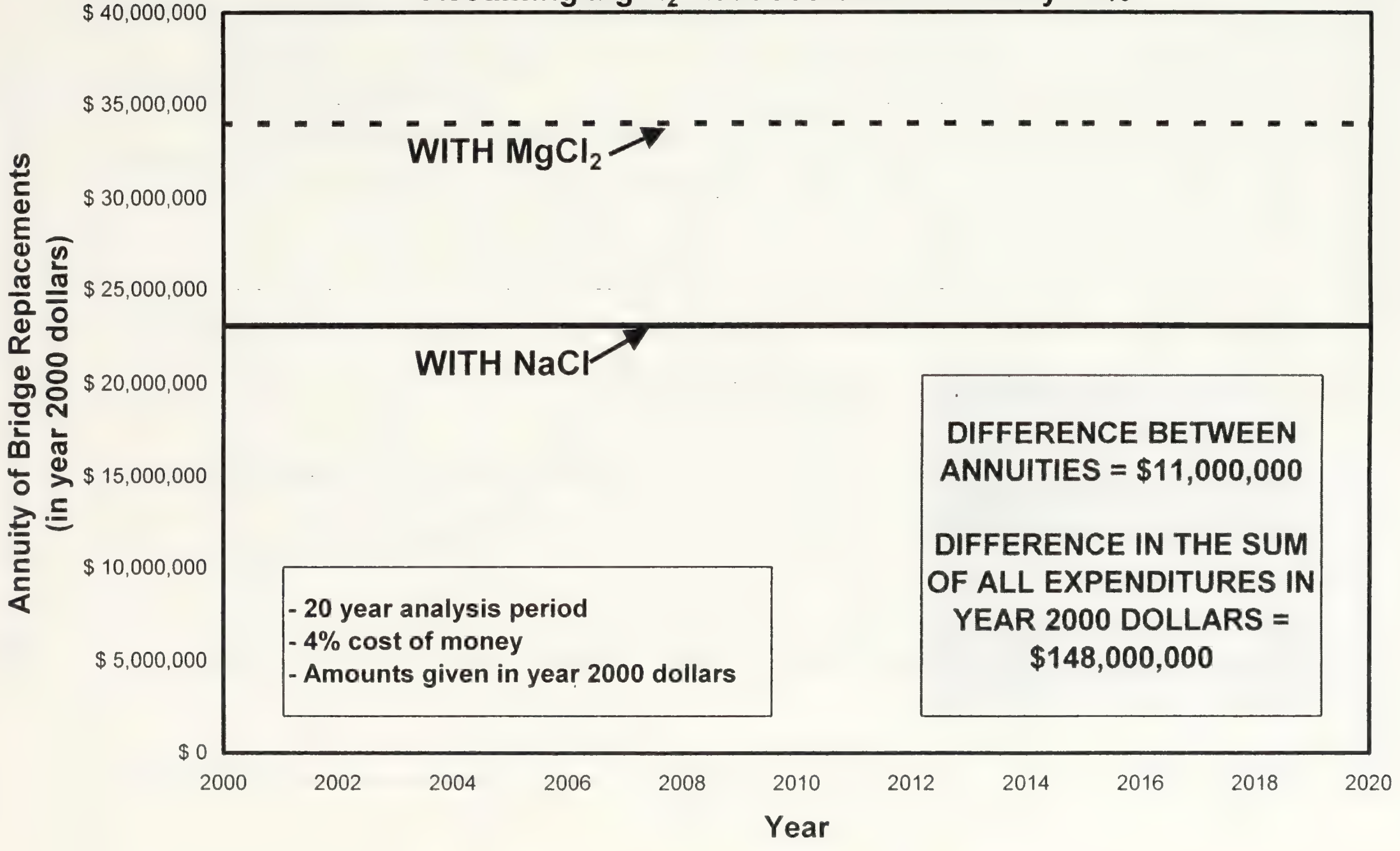
	Expenditure Year	2000	2005	2010	2015
Option 1	Expenditure Description	Bridge Replacements	Bridge Replacements	Bridge Replacements	Bridge Replacements
With $MgCl_2$	Expenditure (Current $)	$ 80,053,800	$ 67,255,450	$ 269,722,150	$ 258,867,300
	Present Worth	$ 80,053,800	$ 55,279,077	$ 182,214,620	$ 143,739,823
Option 2	Expenditure Description	Bridge Replacements	Bridge Replacements	Bridge Replacements	Bridge Replacements
Without $MgCl_2$	Expenditure (Current $)	$ 69,867,100	$ 41,582,850	$ 144,870,100	$ 201,055,650
	Present Worth	$ 69,867,100	$ 34,178,072	$ 97,869,049	$ 111,639,066

	Sum of Present Worths	**Annuity**
Option 1	**$ 461,287,320**	**$ 33,942,328**
Option 2	**$ 313,553,286**	**$ 23,071,800**

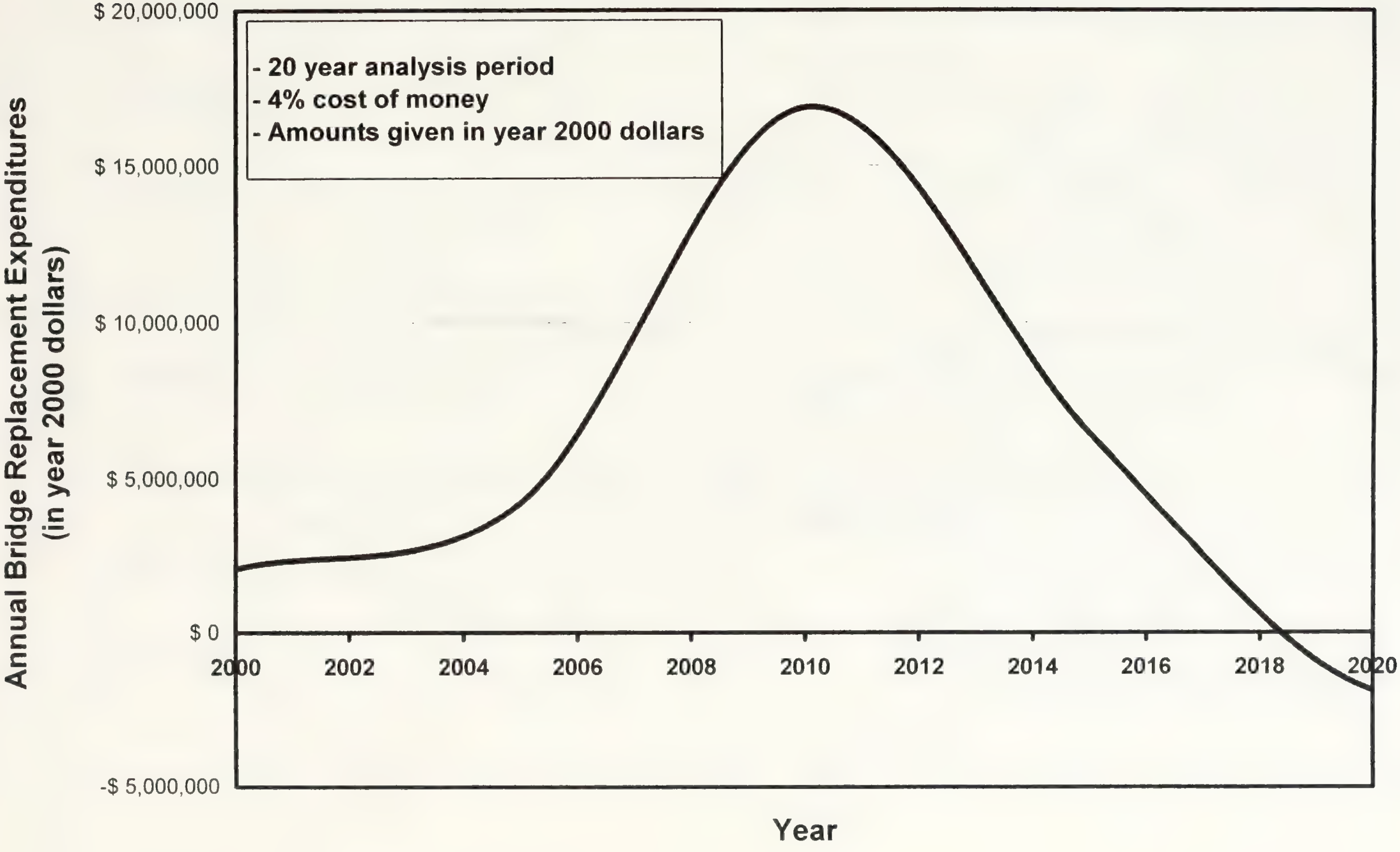
Difference	**$ 147,734,034**	**$ 10,870,529**

Reid Crowther

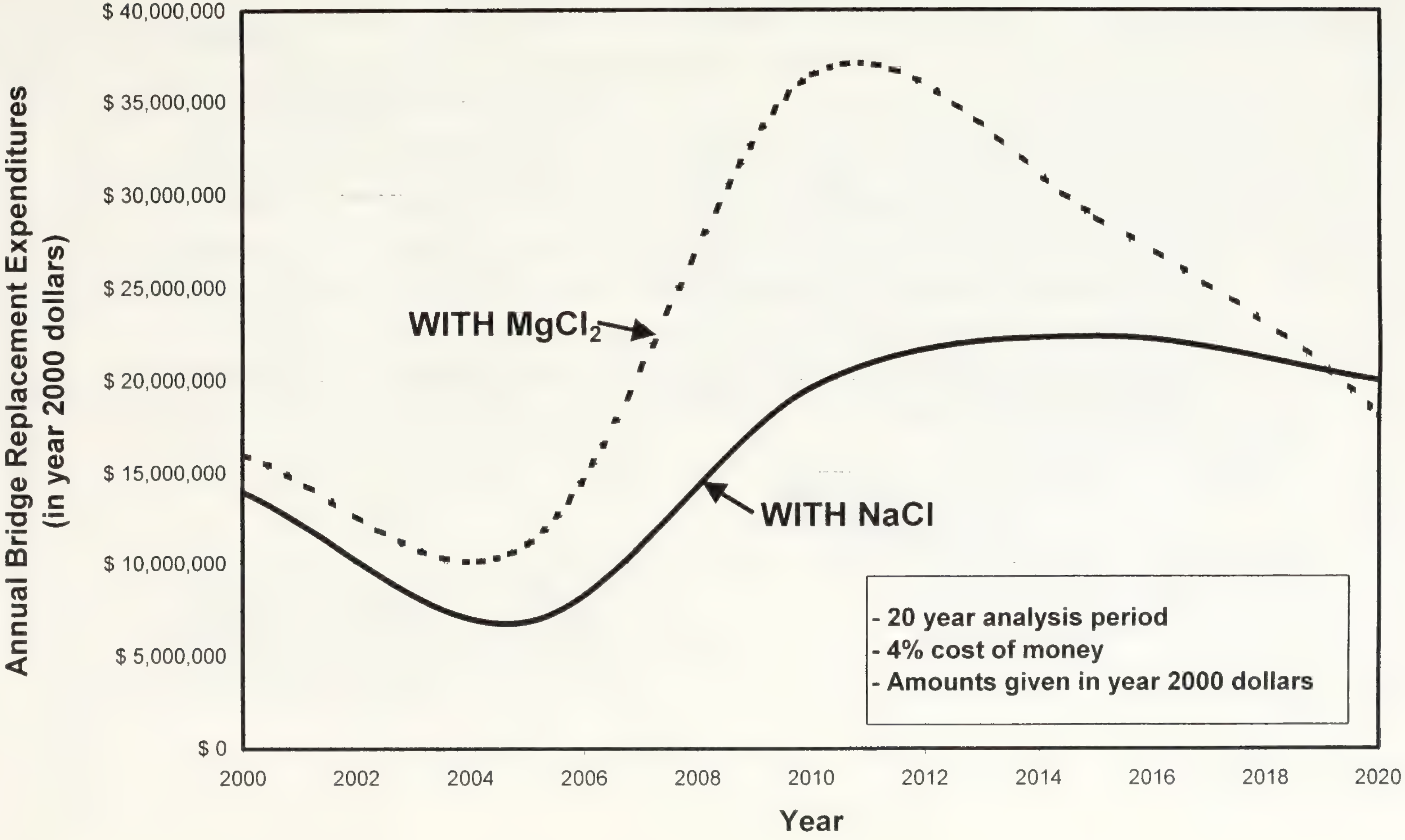
Future Average Bridge Replacement Needs for all Currently Treated Bridges
Assuming $MgCl_2$ Reduces Service Life by 20%



Difference in Annual Bridge Replacement Needs If Entire System Treated with $MgCl_2$ vs NaCl Assuming $MgCl_2$ Reduces Service Life by 20%



Future Annual Bridge Replacement Needs Entire System Treated
Assuming $MgCl_2$ Reduces Service Life by 20%



Present Worth Analysis:
Future Replacement Needs of all Currently Treated Bridges
($MgCl_2$ decreases remaining life by 25%)

Assumptions:

4% = Value of Money (difference between bank interest rate and inflation rate)
2000 = Current Year (for analysis purposes)
20 = Analysis Period (years)

	Expenditure Year	2000	2005	2010	2015
Option 1	Expenditure Description	Bridge Replacements	Bridge Replacements	Bridge Replacements	Bridge Replacements
With $MgCl_2$	Expenditure (Current $)	$ 80,053,800	$ 96,119,300	$ 281,202,600	$ 239,099,950
	Present Worth	$ 80,053,800	$ 79,003,058	$ 189,970,401	$ 132,763,715
Option 2	Expenditure Description	Bridge Replacements	Bridge Replacements	Bridge Replacements	Bridge Replacements
Without $MgCl_2$	Expenditure (Current $)	$ 69,867,100	$ 41,582,850	$ 144,870,100	$ 201,055,650
	Present Worth	$ 69,867,100	$ 34,178,072	$ 97,869,049	$ 111,639,066

	Sum of Present Worths	**Annuity**
Option 1	**$ 481,790,974**	**$ 35,451,023**
Option 2	**$ 313,553,286**	**$ 23,071,800**
Difference	**$ 168,237,688**	**$ 12,379,224**

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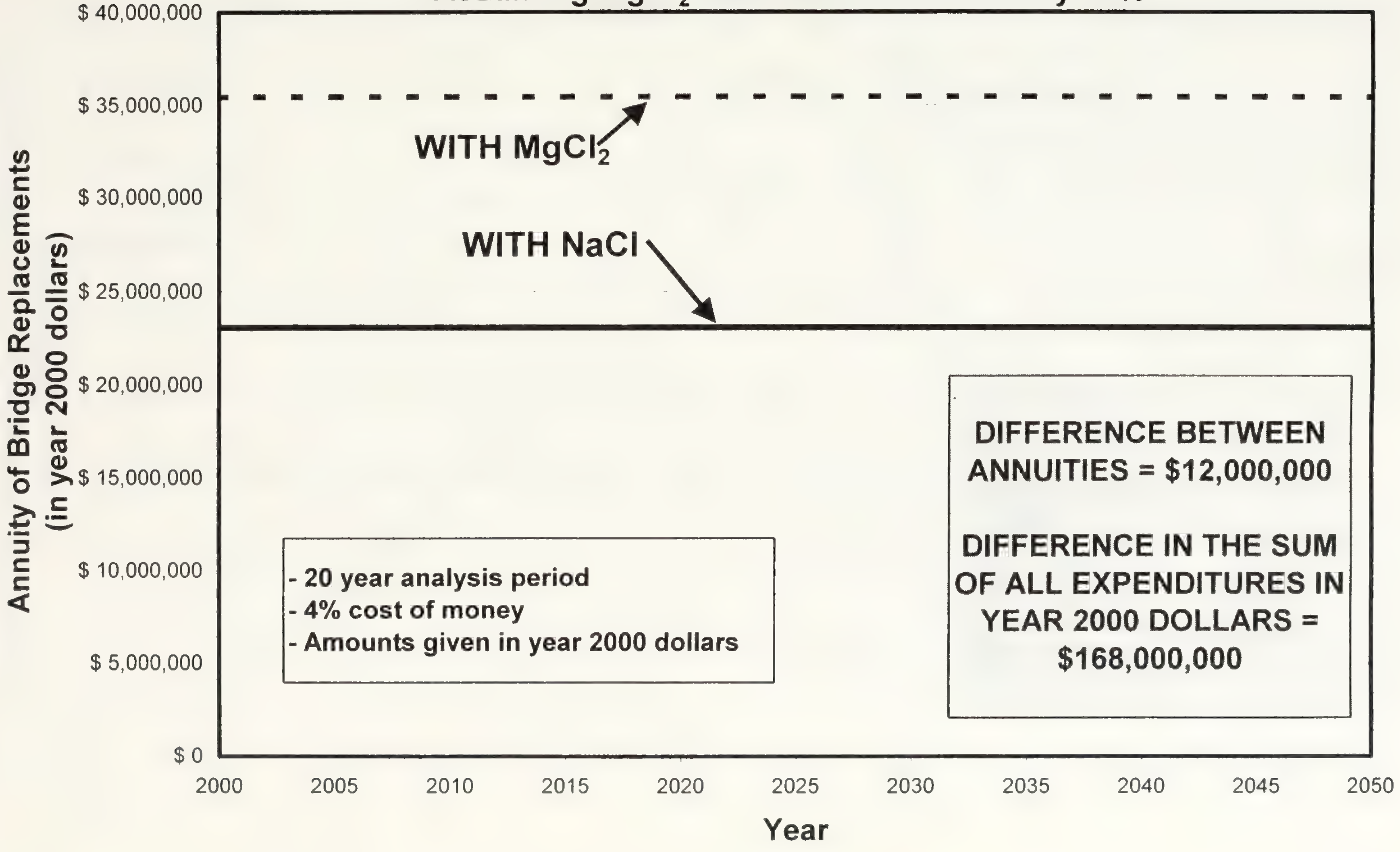
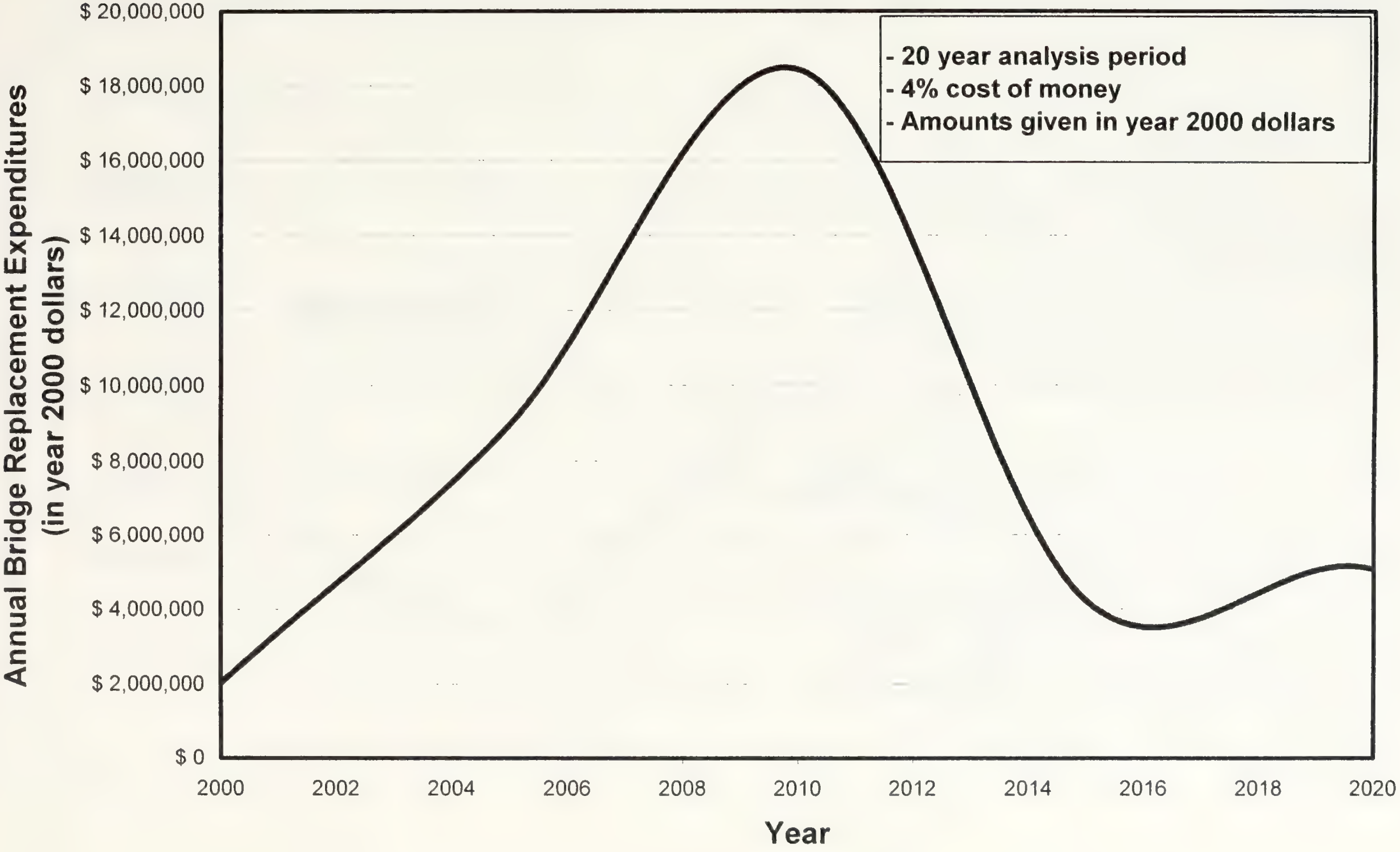
Future Average Bridge Replacement Needs for all Currently Treated Bridges
Assuming $MgCl_2$ Reduces Service Life by 25%



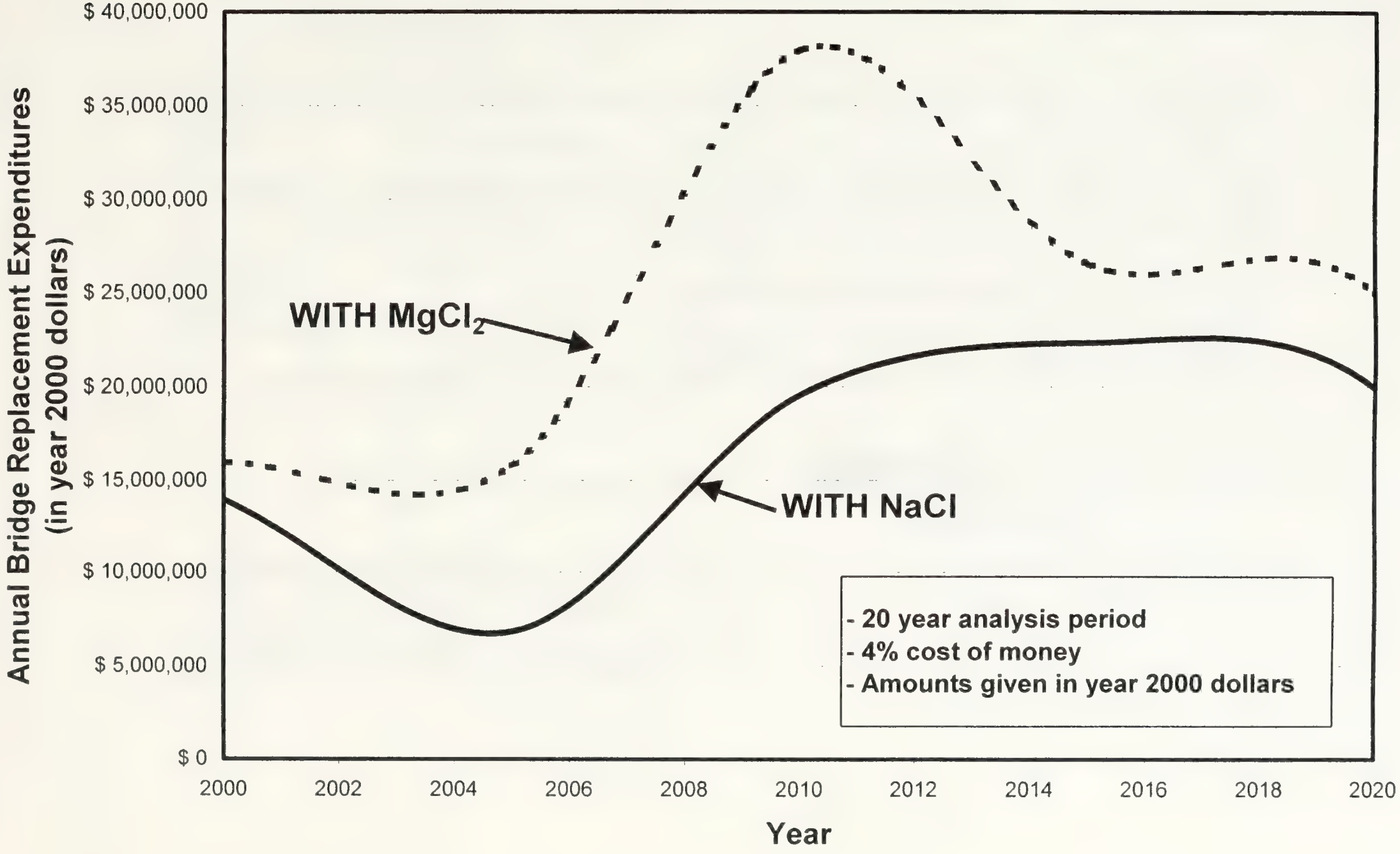
- 20 year analysis period
- 4% cost of money
- Amounts given in year 2000 dollars

DIFFERENCE BETWEEN ANNUITIES = $12,000,000

DIFFERENCE IN THE SUM OF ALL EXPENDITURES IN YEAR 2000 DOLLARS = $168,000,000


Difference in Annual Bridge Replacement Needs If Entire System Treated with $MgCl_2$ vs NaCl Assuming $MgCl_2$ Reduces Service Life by 25%

- 20 year analysis period
- 4% cost of money
- Amounts given in year 2000 dollars



Future Annual Bridge Replacement Needs Entire System Treated Assuming $MgCl_2$ Reduces Service Life by 25%

- 20 year analysis period
- 4% cost of money
- Amounts given in year 2000 dollars

Present Worth Analysis:
Future Replacement Needs of all Currently Treated Bridges
($MgCl_2$ decreases remaining life by 30%)

Assumptions:

4% = Value of Money (difference between bank interest rate and inflation rate)
2000 = Current Year (for analysis purposes)
20 = Analysis Period (years)

	Expenditure Year	2000	2005	2010	2015
Option 1	Expenditure Description	Bridge Replacements	Bridge Replacements	Bridge Replacements	Bridge Replacements
With $MgCl_2$	Expenditure (Current $)	$ 89,237,700	$ 106,563,600	$ 295,008,350	$ 275,261,700
	Present Worth	$ 89,237,700	$ 87,587,511	$ 199,297,071	$ 152,843,051
Option 2	Expenditure Description	Bridge Replacements	Bridge Replacements	Bridge Replacements	Bridge Replacements
Without $MgCl_2$	Expenditure (Current $)	$ 69,867,100	$ 41,582,850	$ 144,870,100	$ 201,055,650
	Present Worth	$ 69,867,100	$ 34,178,072	$ 97,869,049	$ 111,639,066

	Sum of Present Worths	**Annuity**
Option 1	**$ 528,965,333**	**$ 38,922,195**
Option 2	**$ 313,553,286**	**$ 23,071,800**
Difference	**$ 215,412,047**	**$ 15,850,395**

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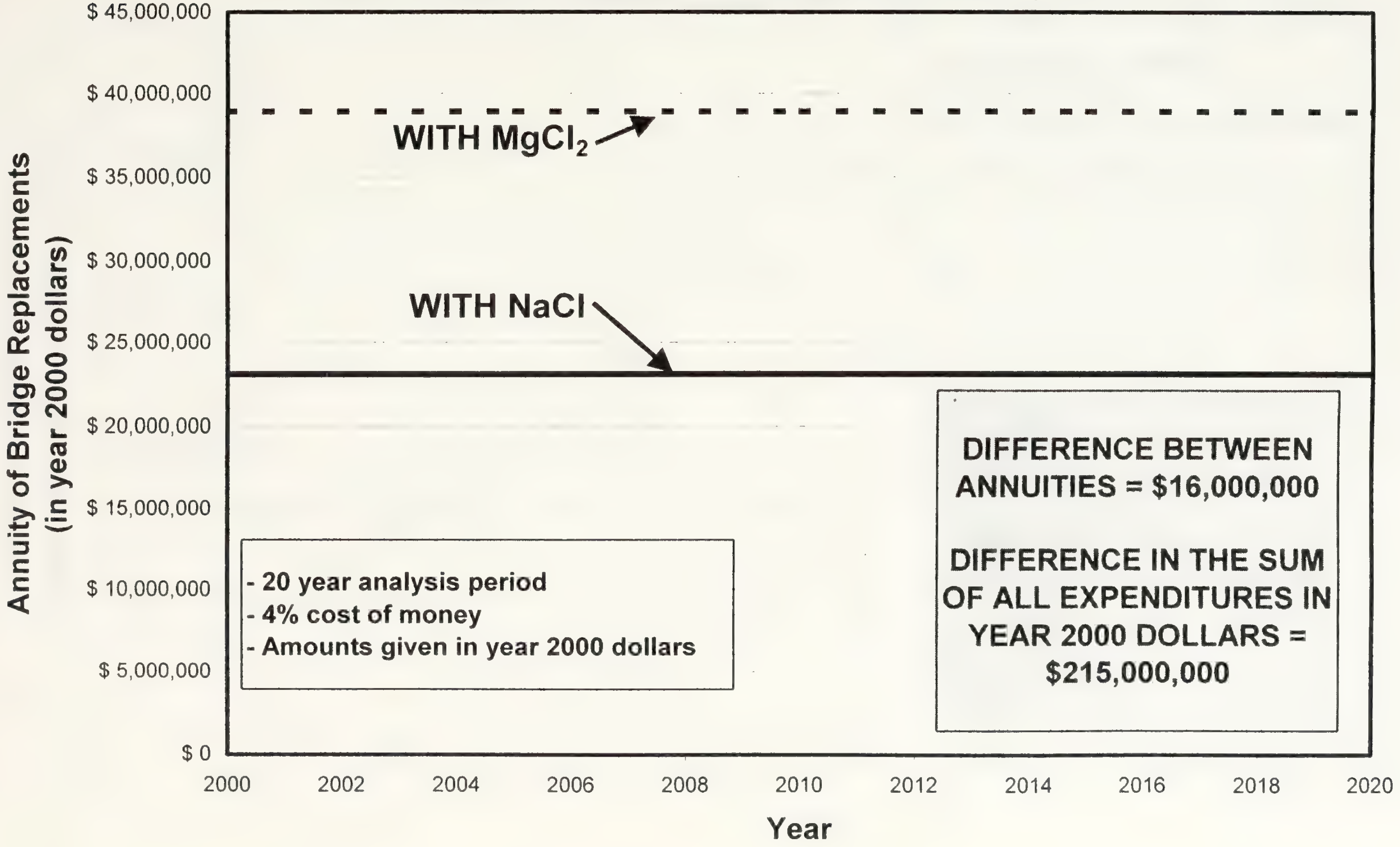
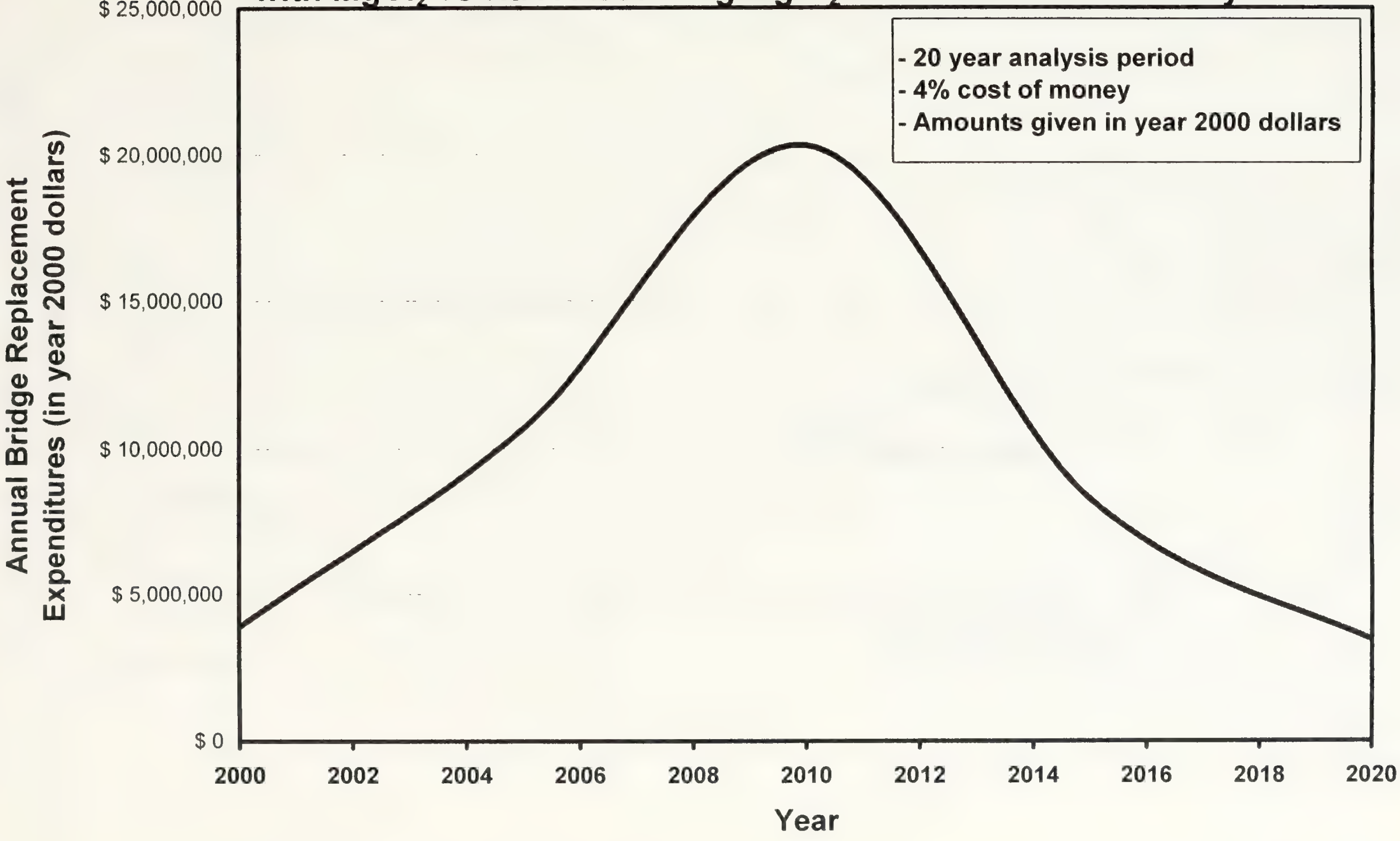
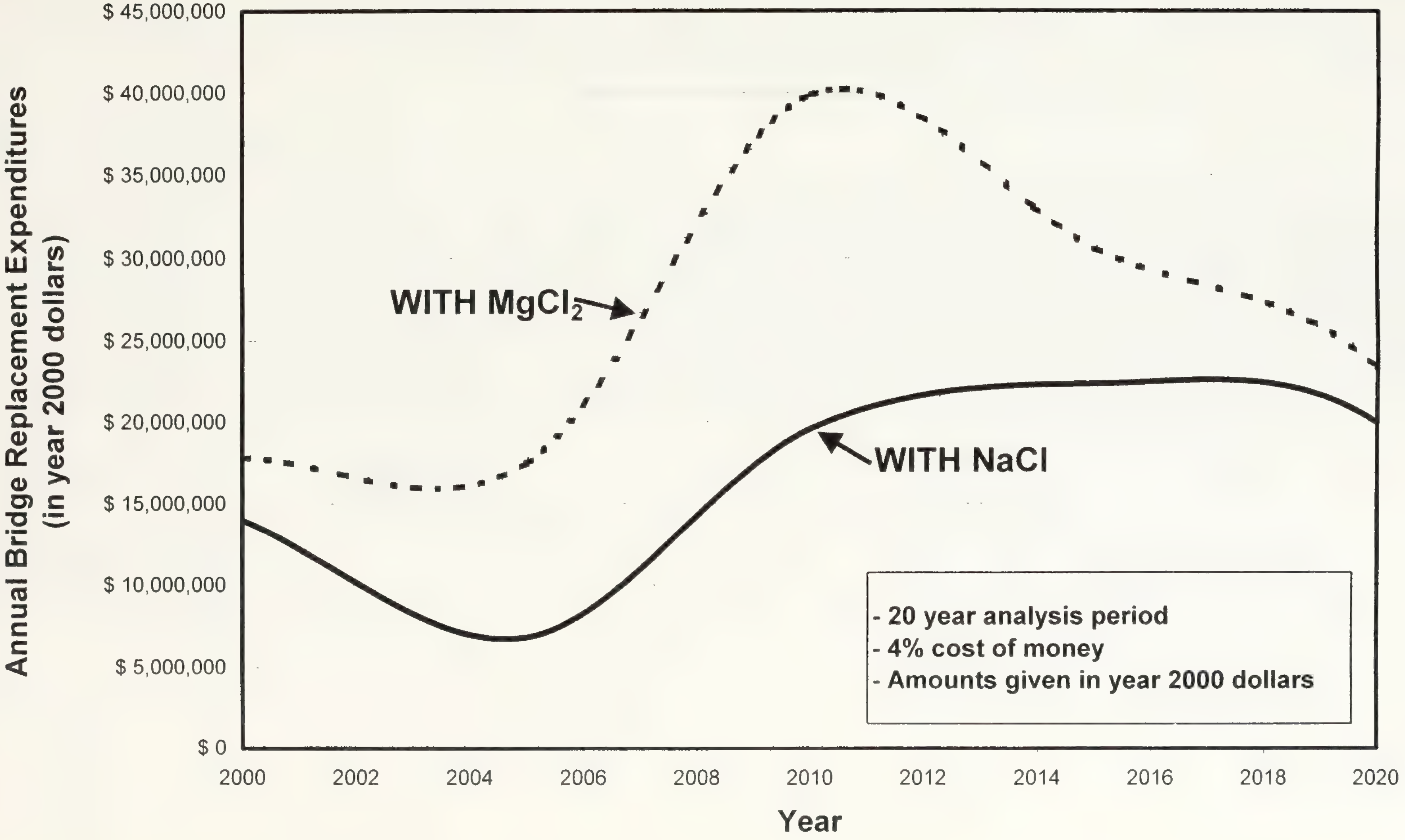


Future Average Bridge Replacement Needs for all Currently Treated Bridges
Assuming $MgCl_2$ Reduces Service Life by 30%

Difference in Annual Bridge Replacement Needs If Entire System Treated
with $MgCl_2$ vs NaCl Assuming $MgCl_2$ Reduces Service Life by 30%



Future Annual Bridge Replacement Needs Entire System Treated
Assuming $MgCl_2$ Reduces Service Life by 30%



Present Worth Analysis:
Future Replacement Needs of all Currently Treated Bridges
($MgCl_2$ decreases remaining life by 20%)

Assumptions:

4% = Value of Money (difference between bank interest rate and inflation rate)
2000 = Current Year (for analysis purposes)
60 = Analysis Period (years)

	Expenditure Year	2000	2005	2010	2015	2020	2025	2030	2035	2040	2045	2050	2055
Option 1 With $MgCl_2$	Expenditure Description	Bridge Replacements	Bridge Replacements	Bridge Replacements	Bridge Replacements	Bridge Replacements	Bridge Replacements	Bridge Replacements	Bridge Replacements	Bridge Replacements	Bridge Replacements	Bridge Replacements	Bridge Replacements
	Expenditure (Current $)	$ 80,053,800	$ 67,255,450	$ 269,722,150	$ 258,867,300	$ 198,074,850	$ 181,777,050	$ 74,605,100	$ 59,967,900	$ 32,580,650	$ 98,818,350	$ 308,441,500	$ 216,274,750
	Present Worth	$ 80,053,800	$ 55,279,077	$ 182,214,620	$ 143,739,823	$ 90,398,776	$ 68,187,626	$ 23,002,145	$ 15,196,794	$ 6,786,192	$ 16,917,545	$ 43,401,610	$ 25,013,367
Option 2 Without $MgCl_2$	Expenditure Description	Bridge Replacements	Bridge Replacements	Bridge Replacements	Bridge Replacements	Bridge Replacements	Bridge Replacements	Bridge Replacements	Bridge Replacements	Bridge Replacements	Bridge Replacements	Bridge Replacements	Bridge Replacements
	Expenditure (Current $)	$ 69,867,100	$ 41,582,850	$ 144,870,100	$ 201,055,650	$ 218,523,000	$ 163,186,150	$ 182,999,500	$ 84,430,700	$ 30,102,400	$ 55,251,750	$ 28,051,950	$ 57,390,750
	Present Worth	$ 69,867,100	$ 34,178,072	$ 97,869,049	$ 111,639,066	$ 99,731,045	$ 61,213,867	$ 56,422,162	$ 21,396,046	$ 6,270,000	$ 9,459,012	$ 3,947,263	$ 6,637,557

	Sum of Present Worths	Annuity
Option 1	$ 750,191,375	$ 33,159,843
Option 2	$ 578,630,237	$ 25,576,524

Difference	$ 171,561,138	$ 7,583,319

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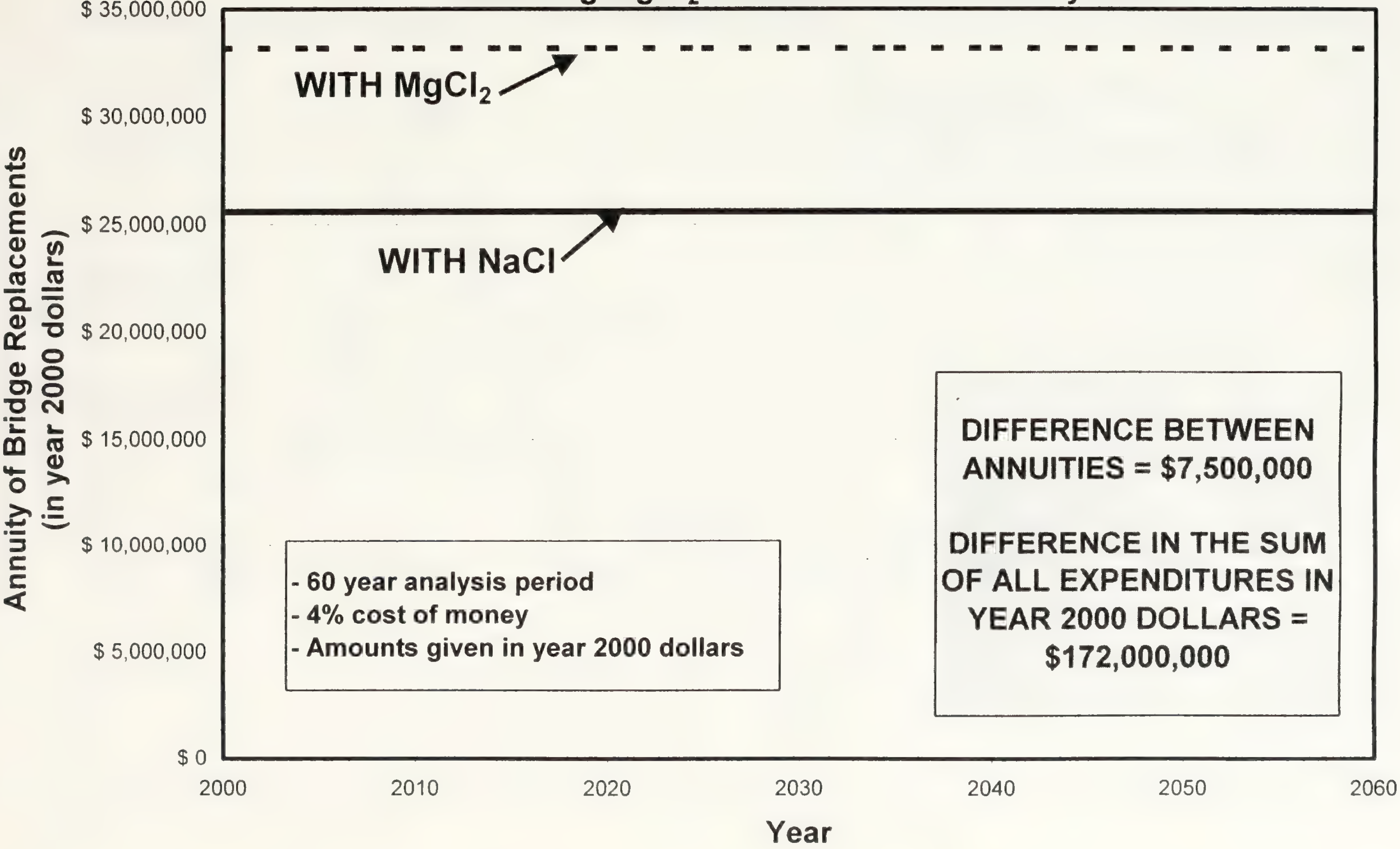
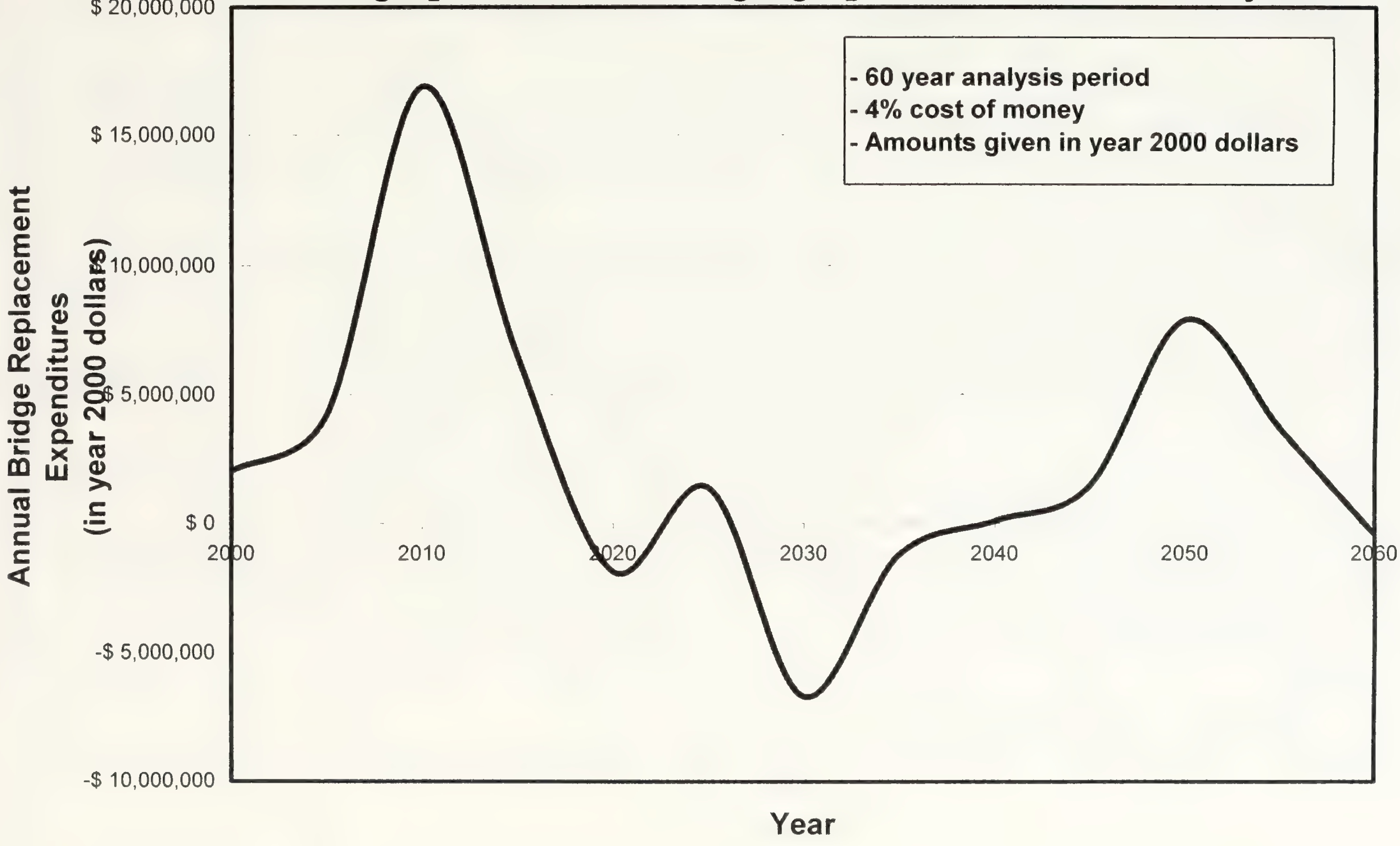
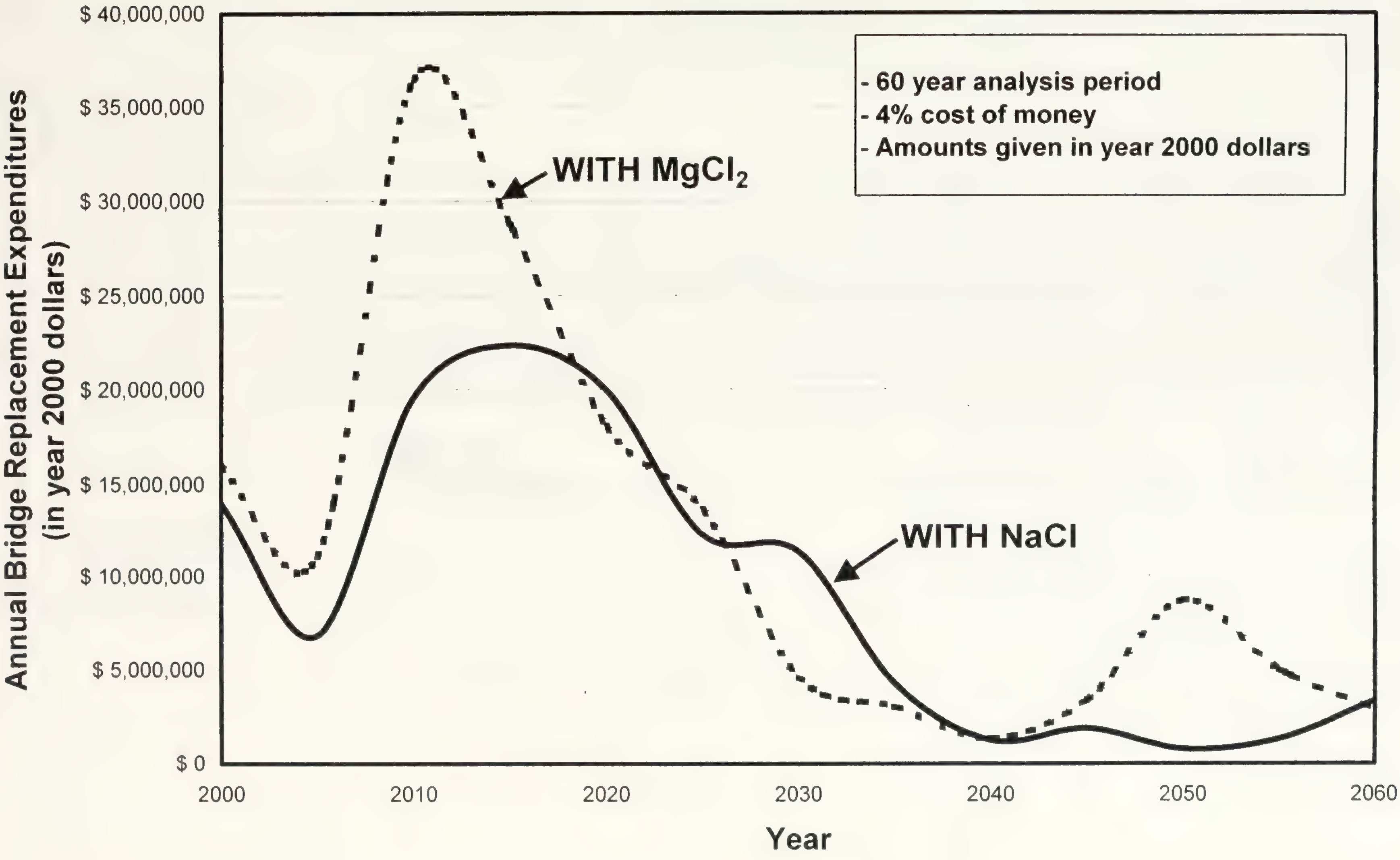
Future Average Bridge Replacement Needs for all Currently Treated Bridges
Assuming $MgCl_2$ Reduces Service Life by 20%



Difference in Annual Bridge Replacement Needs If Entire System Treated with $MgCl_2$ vs NaCl Assuming $MgCl_2$ Reduces Service Life by 20%





Future Annual Bridge Replacement Needs Entire System Treated Assuming $MgCl_2$ Reduces Service Life by 20%

Present Worth Analysis:
Future Replacement Needs of all Currently Treated Bridges
($MgCl_2$ decreases remaining life by 25%)

Assumptions:

4% = Value of Money (difference between bank interest rate and inflation rate)
2000 = Current Year (for analysis purposes)
60 = Analysis Period (years)

	Expenditure Year	2000	2005	2010	2015	2020	2025	2030	2035	2040	2045	2050	2055
Option 1	Expenditure Description	Bridge Replacements	Bridge Replacements	Bridge Replacements	Bridge Replacements	Bridge Replacements	Bridge Replacements	Bridge Replacements	Bridge Replacements	Bridge Replacements	Bridge Replacements	Bridge Replacements	Bridge Replacements
With $MgCl_2$	Expenditure (Current $)	$ 80,053,800	$ 96,119,300	$ 281,202,600	$ 239,099,950	$ 274,063,400	$ 135,897,800	$ 47,368,500	$ 47,707,750	$ 58,127,900	$ 224,147,650	$ 293,665,150	$ 148,519,050
	Present Worth	$ 80,053,800	$ 79,003,058	$ 189,970,401	$ 132,763,715	$ 125,078,958	$ 50,977,548	$ 14,604,593	$ 12,089,882	$ 12,107,405	$ 38,373,722	$ 41,322,391	$ 17,177,047
Option 2	Expenditure Description	Bridge Replacements	Bridge Replacements	Bridge Replacements	Bridge Replacements	Bridge Replacements	Bridge Replacements	Bridge Replacements	Bridge Replacements	Bridge Replacements	Bridge Replacements	Bridge Replacements	Bridge Replacements
Without $MgCl_2$	Expenditure (Current $)	$ 69,867,100	$ 41,582,850	$ 144,870,100	$ 201,055,650	$ 218,523,000	$ 163,186,150	$ 182,999,500	$ 84,430,700	$ 30,102,400	$ 55,251,750	$ 28,051,950	$ 57,390,750
	Present Worth	$ 69,867,100	$ 34,178,072	$ 97,869,049	$ 111,639,066	$ 99,731,045	$ 61,213,867	$ 56,422,162	$ 21,396,046	$ 6,270,000	$ 9,459,012	$ 3,947,263	$ 6,637,557

	Sum of Present Worths	Annuity
Option 1	$ 793,522,519	$ 35,075,160
Option 2	$ 578,630,237	$ 25,576,524

Difference	$ 214,892,283	$ 9,498,635

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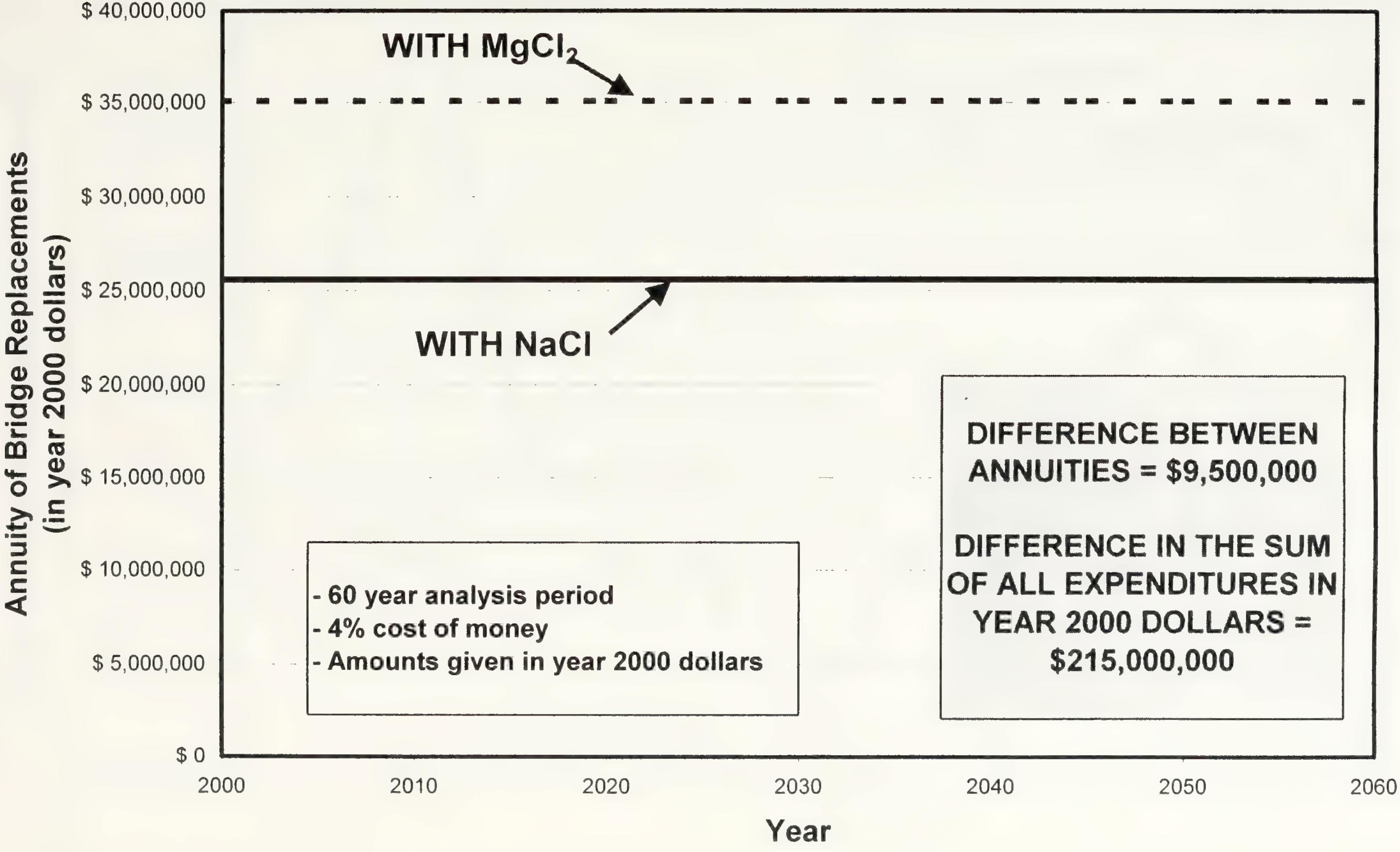
Future Average Bridge Replacement Needs for all Currently Treated Bridges

Assuming $MgCl_2$ Reduces Service Life by 25%

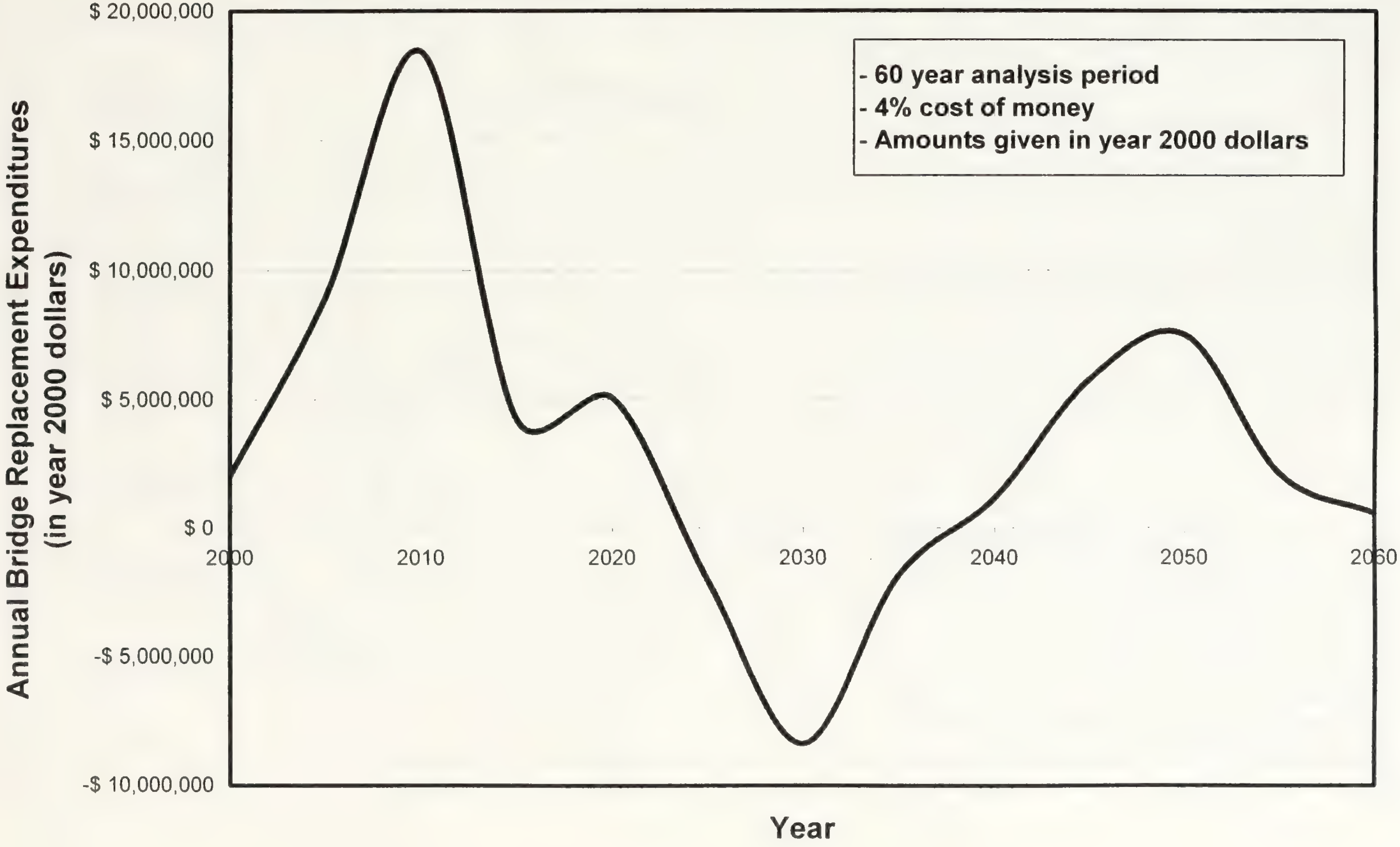


- 60 year analysis period
- 4% cost of money
- Amounts given in year 2000 dollars

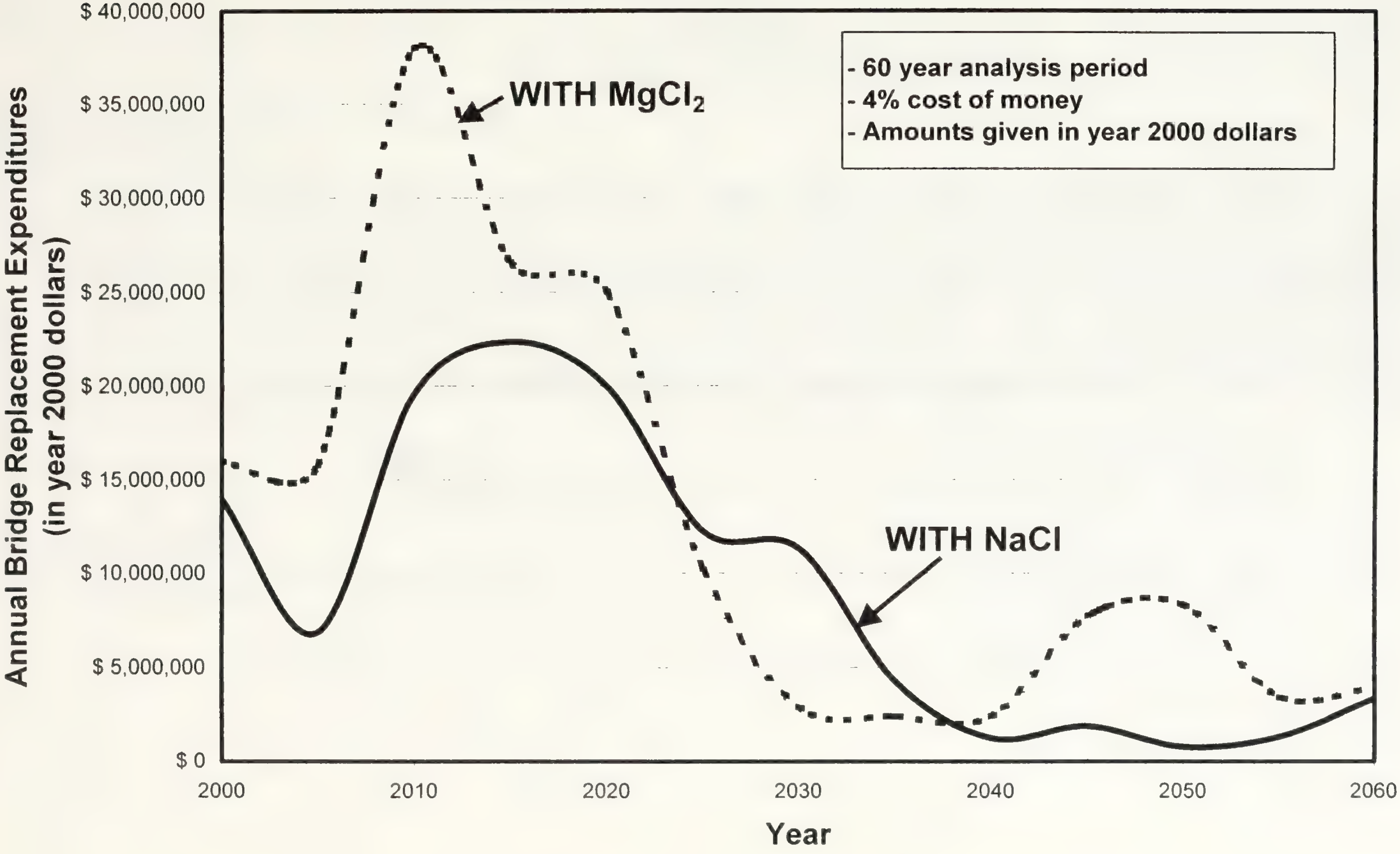
DIFFERENCE BETWEEN ANNUITIES = $9,500,000

DIFFERENCE IN THE SUM OF ALL EXPENDITURES IN YEAR 2000 DOLLARS = $215,000,000

Difference in Annual Bridge Replacement Needs If Entire System Treated with $MgCl_2$ vs NaCl Assuming $MgCl_2$ Reduces Service Life by 25%



Future Annual Bridge Replacement Needs Entire System Treated Assuming $MgCl_2$ Reduces Service Life by 25%



Present Worth Analysis:
Future Replacement Needs of all Currently Treated Bridges
($MgCl_2$ decreases remaining life by 30%)

Assumptions:

4% = Value of Money (difference between bank interest rate and inflation rate)
2000 = Current Year (for analysis purposes)
60 = Analysis Period (years)

	Expenditure Year	2000	2005	2010	2015	2020	2025	2030	2035	2040	2045	2050	2055
Option 1	Expenditure Description	Bridge Replacements	Bridge Replacements	Bridge Replacements	Bridge Replacements	Bridge Replacements	Bridge Replacements	Bridge Replacements	Bridge Replacements	Bridge Replacements	Bridge Replacements	Bridge Replacements	Bridge Replacements
With $MgCl_2$	Expenditure (Current $)	$ 89,237,700	$ 106,563,600	$ 295,008,350	$ 275,261,700	$ 256,013,000	$ 103,556,350	$ 64,682,900	$ 34,625,350	$ 149,664,450	$ 316,712,300	$ 204,980,600	$ 206,928,700
	Present Worth	$ 89,237,700	$ 87,587,511	$ 199,297,071	$ 152,843,051	$ 116,840,991	$ 38,845,727	$ 19,942,946	$ 8,774 599	$ 31,173,465	$ 54,220,643	$ 28,843,356	$ 23,932,445
Option 2	Expenditure Description	Bridge Replacements	Bridge Replacements	Bridge Replacements	Bridge Replacements	Bridge Replacements	Bridge Replacements	Bridge Replacements	Bridge Replacements	Bridge Replacements	Bridge Replacements	Bridge Replacements	Bridge Replacements
Without $MgCl_2$	Expenditure (Current $)	$ 69,867,100	$ 41,582,850	$ 144,870,100	$ 201,055,650	$ 218,523,000	$ 163,186,150	$ 182,999,500	$ 84,430,700	$ 30,102,400	$ 55,251,750	$ 28,051,950	$ 57,390,750
	Present Worth	$ 69,867,100	$ 34,178,072	$ 97,869,049	$ 111,639,066	$ 99,731,045	$ 61,213,867	$ 56,422,162	$ 21,396,046	$ 6,270,000	$ 9,459,012	$ 3,947,263	$ 6,637,557

	Sum of Present Worths	Annuity
Option 1	$ 851,539,506	$ 37,639,617
Option 2	$ 578,630,237	$ 25,576,524

Difference	$ 272,909,269	$ 12,063,093

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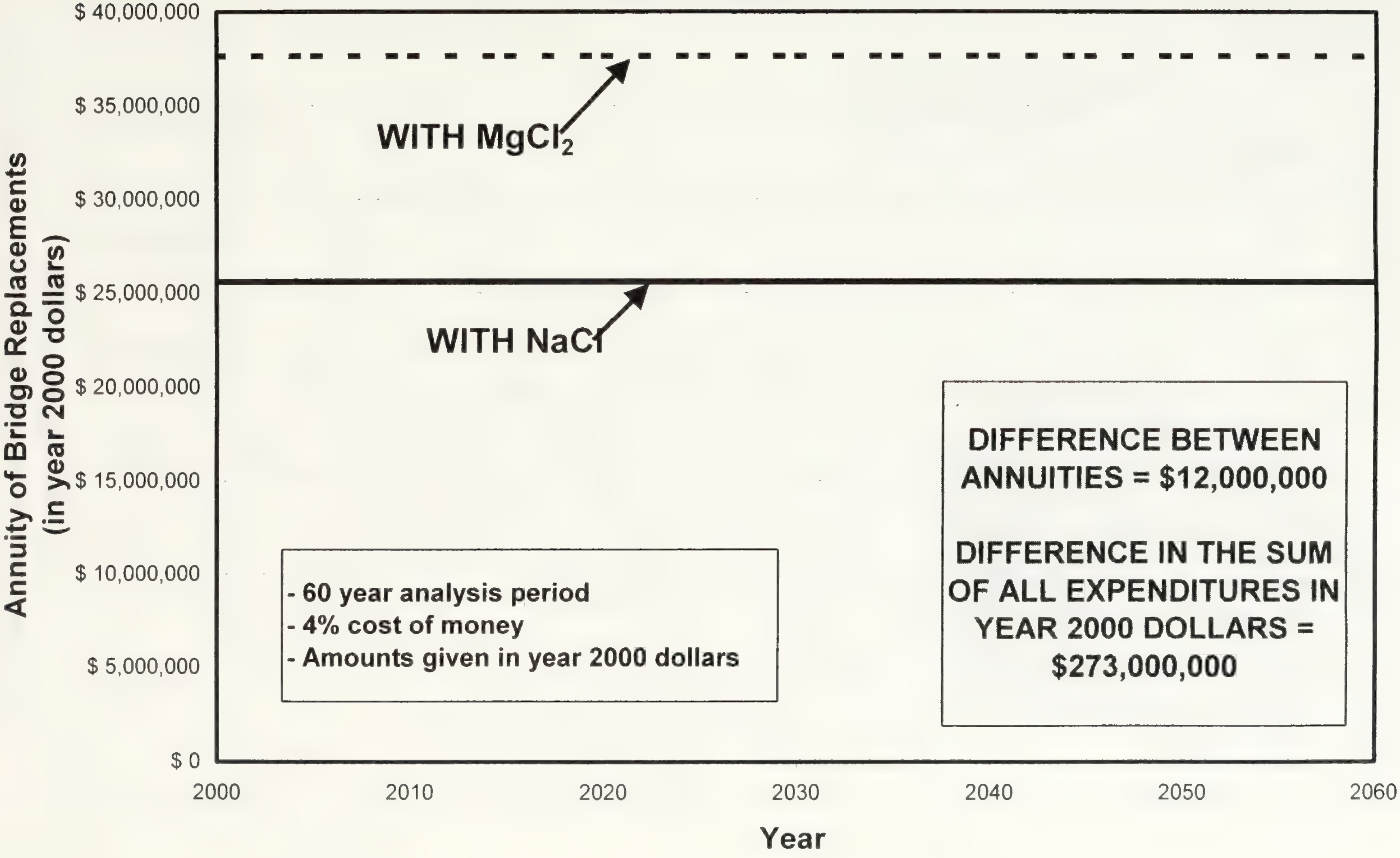
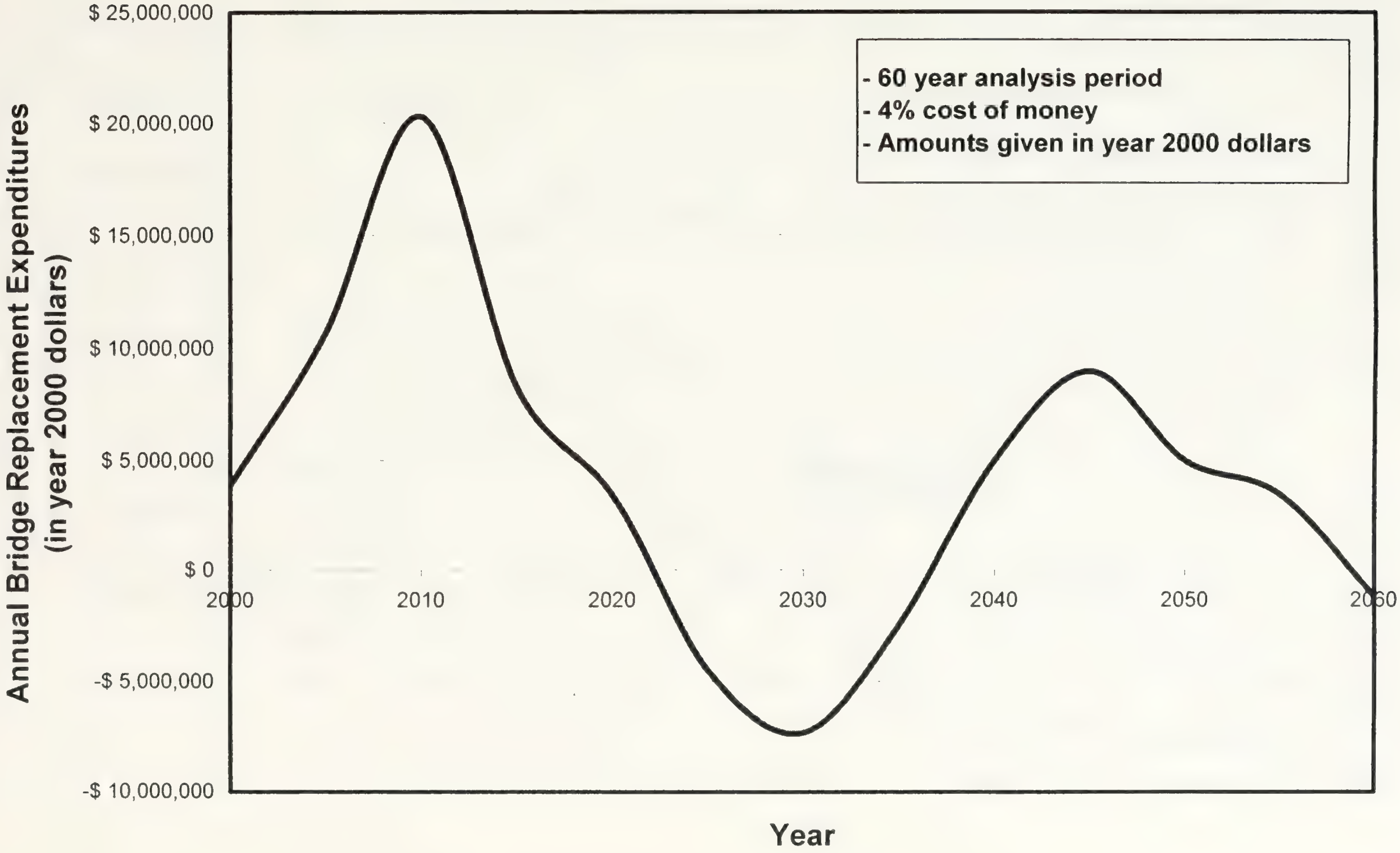
Future Average Bridge Replacement Needs for all Currently Treated Bridges
Assuming $MgCl_2$ Reduces Service Life by 30%



- 60 year analysis period
- 4% cost of money
- Amounts given in year 2000 dollars

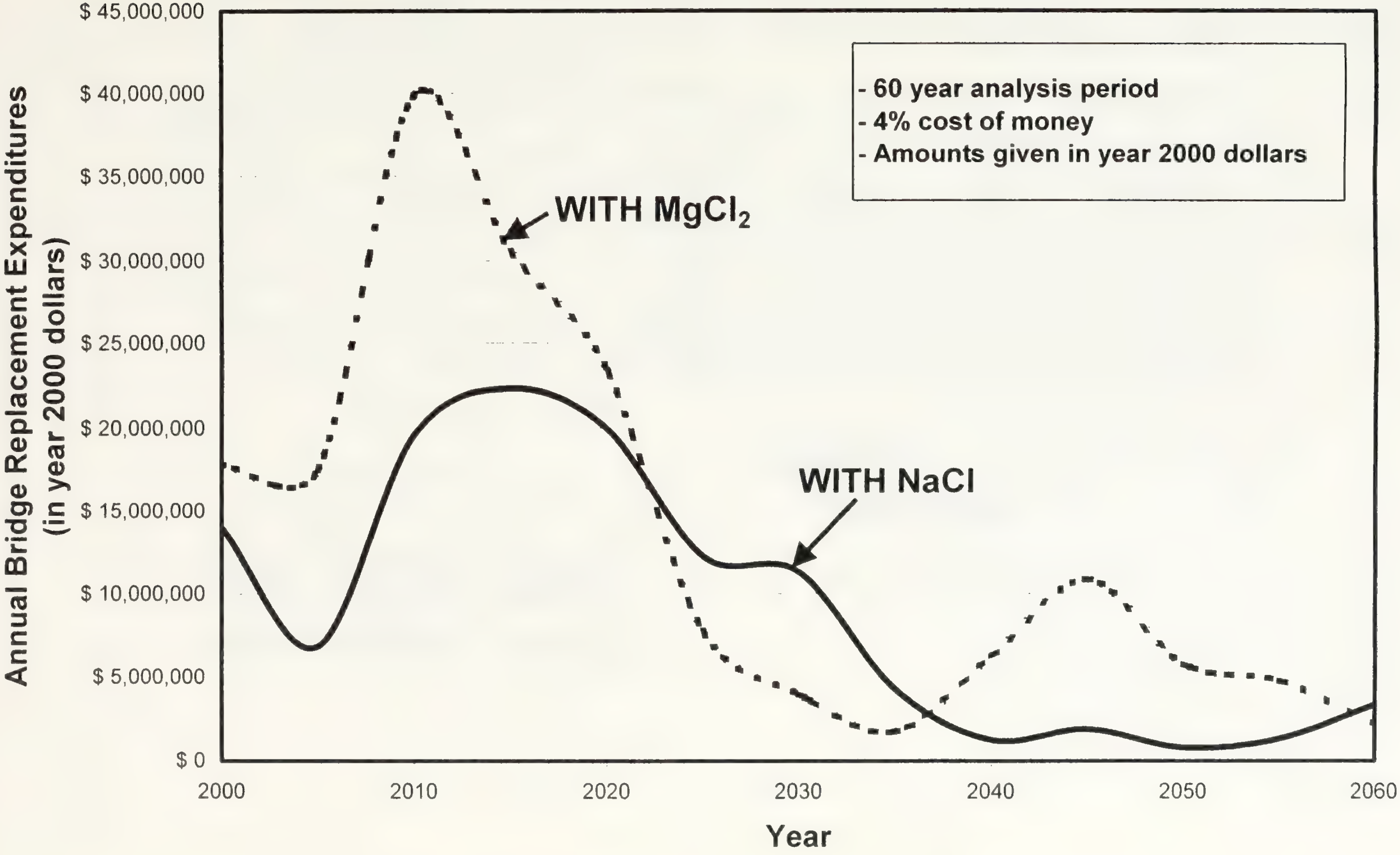
DIFFERENCE BETWEEN ANNUITIES = $12,000,000

DIFFERENCE IN THE SUM OF ALL EXPENDITURES IN YEAR 2000 DOLLARS = $273,000,000



Difference in Annual Bridge Replacement Needs If Entire System Treated with $MgCl_2$ vs NaCl Assuming $MgCl_2$ Reduces Service Life by 30%

Future Annual Bridge Replacement Needs Entire System Treated Assuming $MgCl_2$ Reduces Service Life by 30%



Present Worth Analysis:
Future Replacement Needs of all Currently Treated Bridges
($MgCl_2$ decreases remaining life by 20%)
Future dollars with 6% increase for inflation & increased standards

Assumptions:

-2% = Value of Money; difference between bank interest rate and inflation rate
2000 = Current Year (for analysis purposes) (this is equal to 6% for inflation and increased standards)
20 = Analysis Period (years)

	Expenditure Year	2000	2005	2010	2015
Option 1	Expenditure Description	Bridge Replacements	Bridge Replacements	Bridge Replacements	Bridge Replacements
With $MgCl_2$	Expenditure (Current $)	$ 80,053,800	$ 67,255,450	$ 269,722,150	$ 258,867,300
	Present Worth	$ 80,053,800	$ 74,404,141	$ 330,107,853	$ 350,498,415
Option 2	Expenditure Description	Bridge Replacements	Bridge Replacements	Bridge Replacements	Bridge Replacements
Without $MgCl_2$	Expenditure (Current $)	$ 69,867,100	$ 41,582,850	$ 144,870,100	$ 201,055,650
	Present Worth	$ 69,867,100	$ 46,002,758	$ 177,303,783	$ 272,223,207

	Sum of Present Worths	**Annuity**
Option 1	**$ 835,064,209**	**$ 33,544,458**
Option 2	**$ 565,396,849**	**$ 22,711,943**
Difference	**$ 269,667,360**	**$ 10,832,515**

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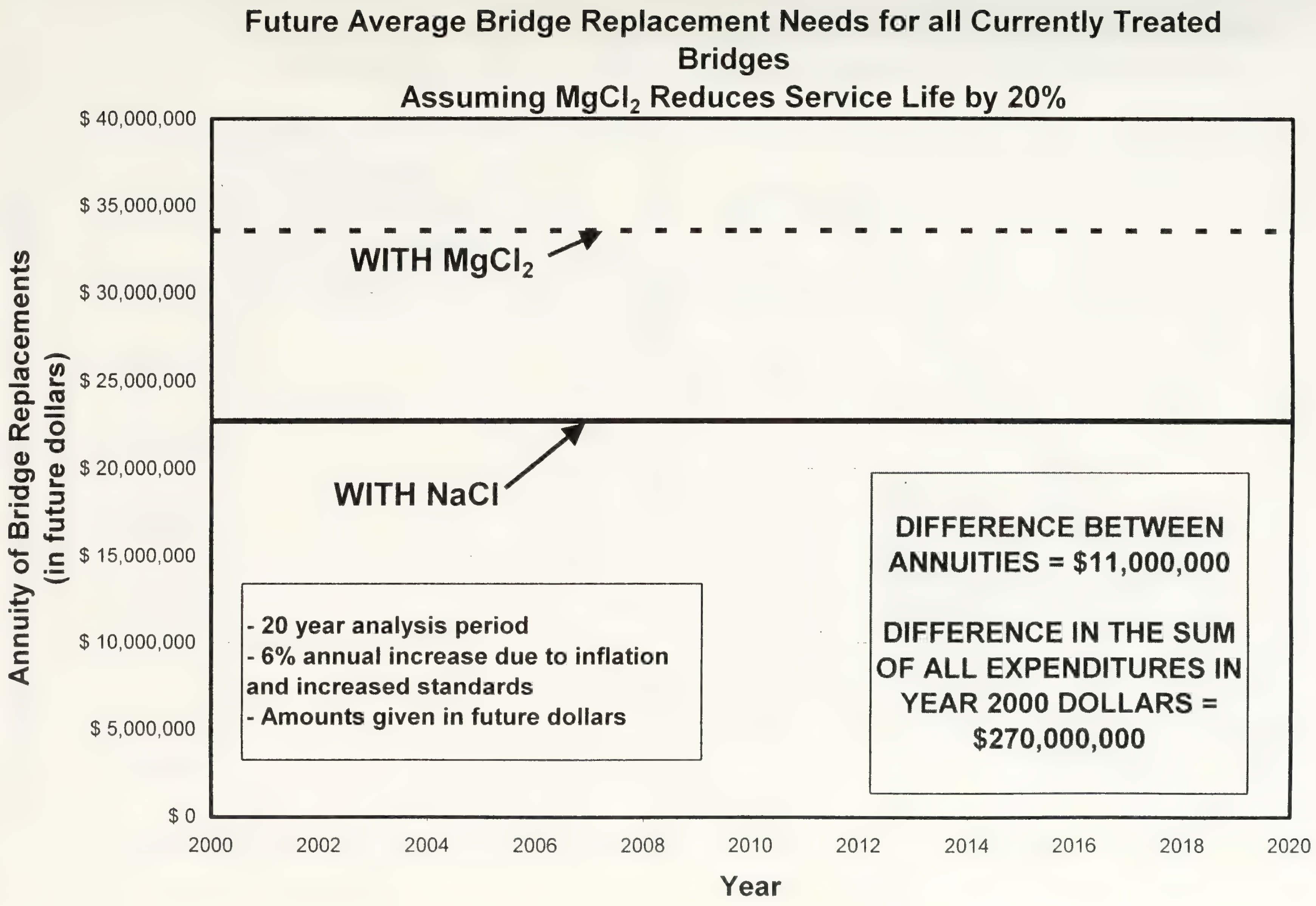
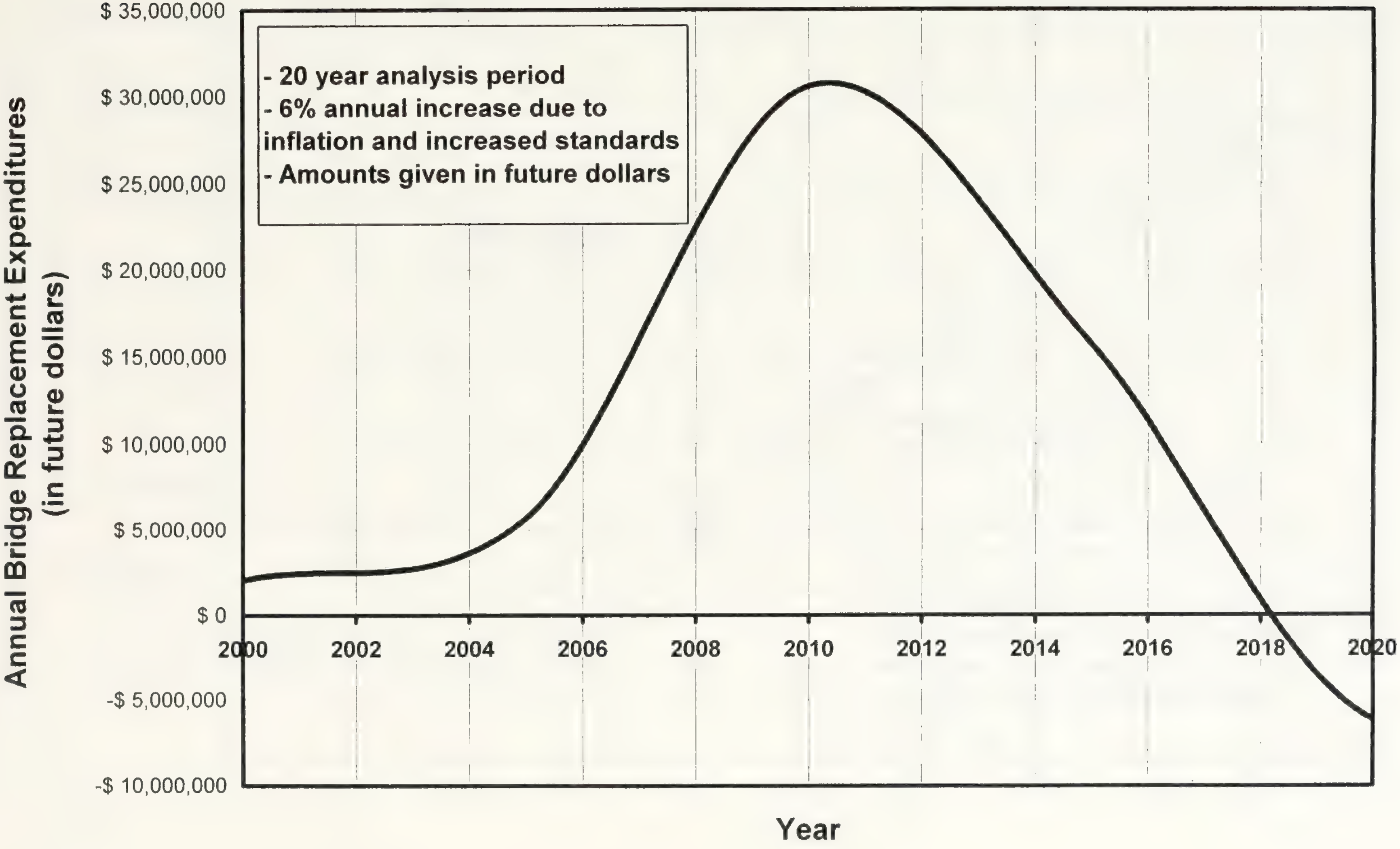
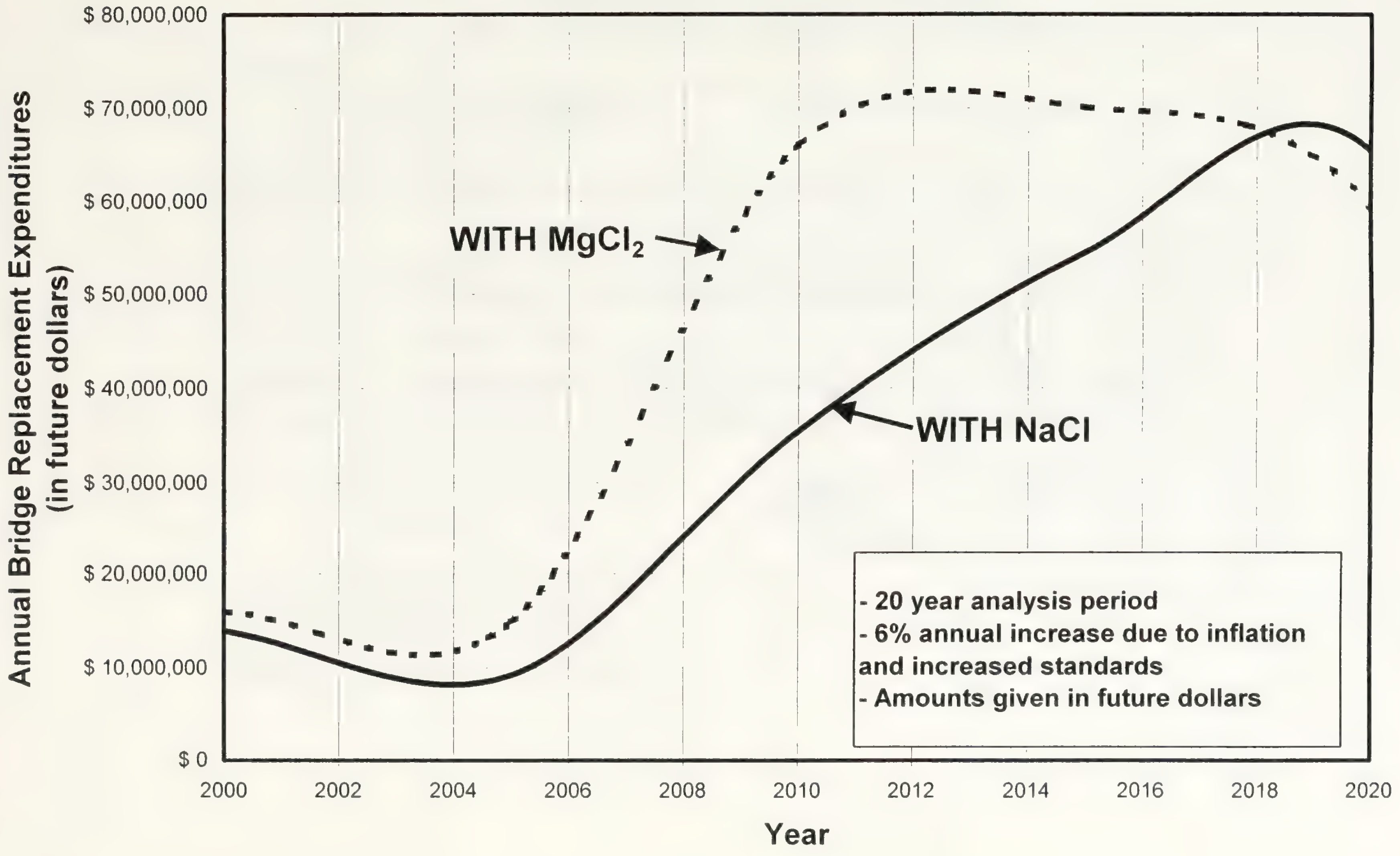

Future Average Bridge Replacement Needs for all Currently Treated Bridges
Assuming $MgCl_2$ Reduces Service Life by 20%
Annuity of Bridge Replacements (in future dollars)
$ 40,000,000
$ 35,000,000
$ 30,000,000
$ 25,000,000
$ 20,000,000
$ 15,000,000
$ 10,000,000
$ 5,000,000
$ 0
2000
2002
2004
2006
2008
2010
2012
2014
2016
2018
2020
Year
WITH $MgCl_2$
WITH NaCl
- 20 year analysis period
- 6% annual increase due to inflation and increased standards
- Amounts given in future dollars
DIFFERENCE BETWEEN ANNUITIES = $11,000,000
DIFFERENCE IN THE SUM OF ALL EXPENDITURES IN YEAR 2000 DOLLARS = $270,000,000

Difference in Annual Bridge Replacement Needs If Entire System Treated with $MgCl_2$ vs NaCl Assuming $MgCl_2$ Reduces Service Life by 20%



Future Annual Bridge Replacement Needs Entire System Treated Assuming $MgCl_2$ Reduces Service Life by 20%



- 20 year analysis period
- 6% annual increase due to inflation and increased standards
- Amounts given in future dollars

Present Worth Analysis:
Future Replacement Needs of all Currently Treated Bridges
($MgCl_2$ decreases remaining life by 25%)
Future dollars with 6% increase for inflation & increased standards

Assumptions:

-2% = Value of Money; difference between bank interest rate and inflation rate
2000 = Current Year (for analysis purposes) (this is equal to 6% inflation and increased standards)
20 = Analysis Period (years)

	Expenditure Year	2000	2005	2010	2015
Option 1	Expenditure Description	Bridge Replacements	Bridge Replacements	Bridge Replacements	Bridge Replacements
With $MgCl_2$	Expenditure (Current $)	$ 80,053,800	$ 96,119,300	$ 281,202,600	$ 239,099,950
	Present Worth	$ 80,053,800	$ 106,335,976	$ 344,158,559	$ 323,734,027
Option 2	Expenditure Description	Bridge Replacements	Bridge Replacements	Bridge Replacements	Bridge Replacements
Without $MgCl_2$	Expenditure (Current $)	$ 69,867,100	$ 41,582,850	$ 144,870,100	$ 201,055,650
	Present Worth	$ 69,867,100	$ 46,002,758	$ 177,303,783	$ 272,223,207

	Sum of Present Worths	**Annuity**
Option 1	**$ 854,282,362**	**$ 34,316,450**
Option 2	**$ 565,396,849**	**$ 22,711,943**
Difference	**$ 288,885,513**	**$ 11,604,506**

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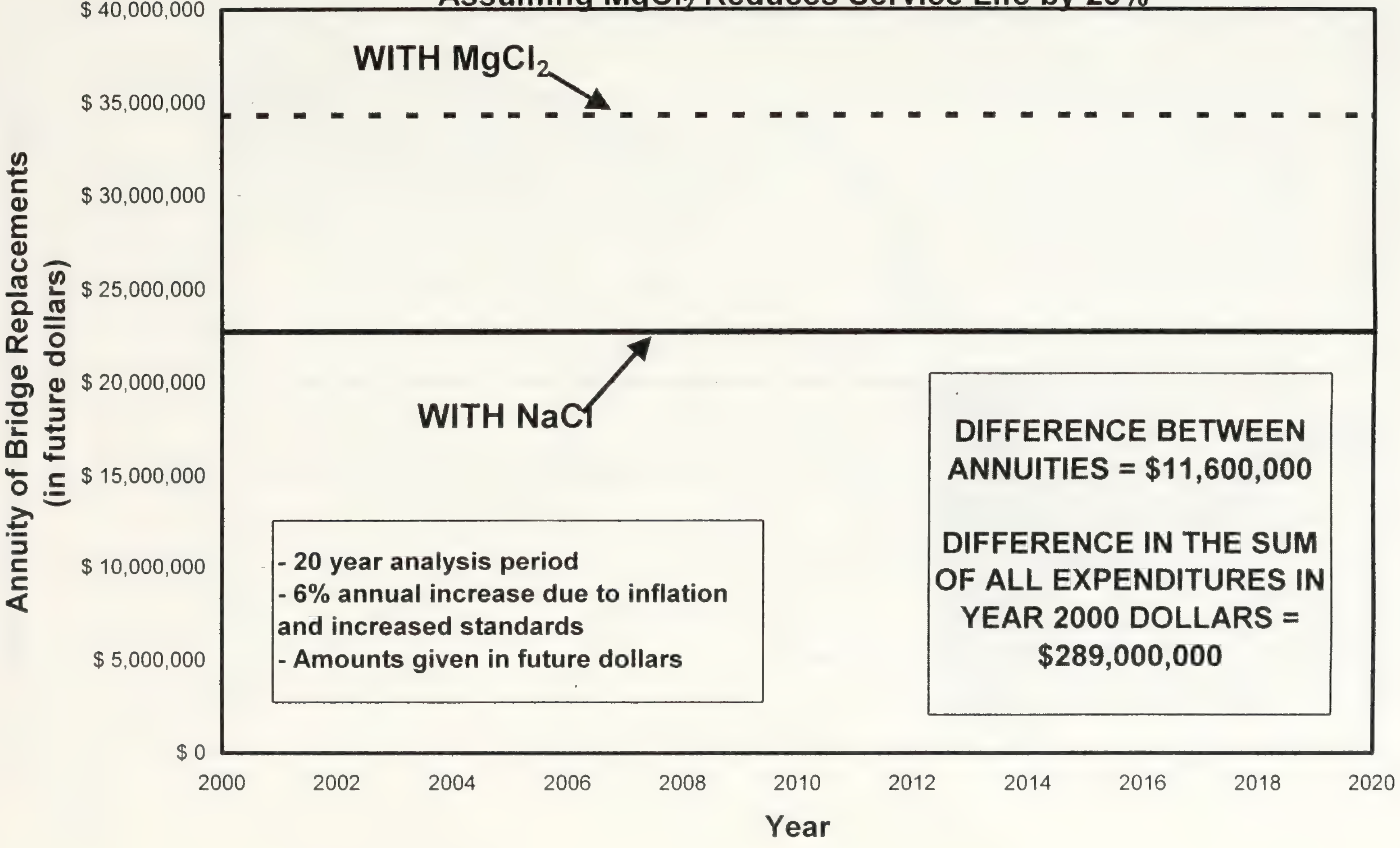
Future Average Bridge Replacement Needs for all Currently Treated Bridges
Assuming $MgCl_2$ Reduces Service Life by 25%

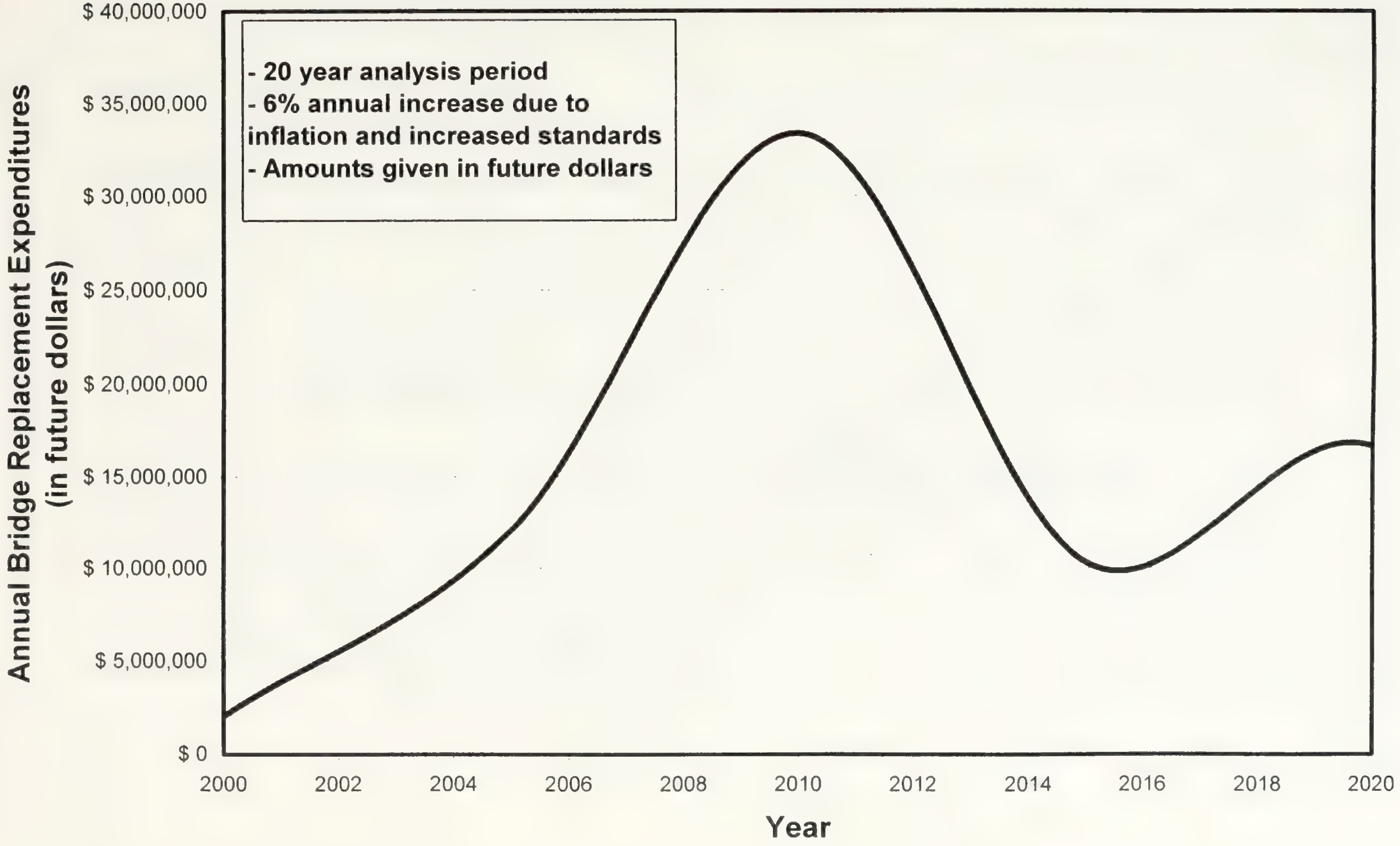


- 20 year analysis period
- 6% annual increase due to inflation and increased standards
- Amounts given in future dollars

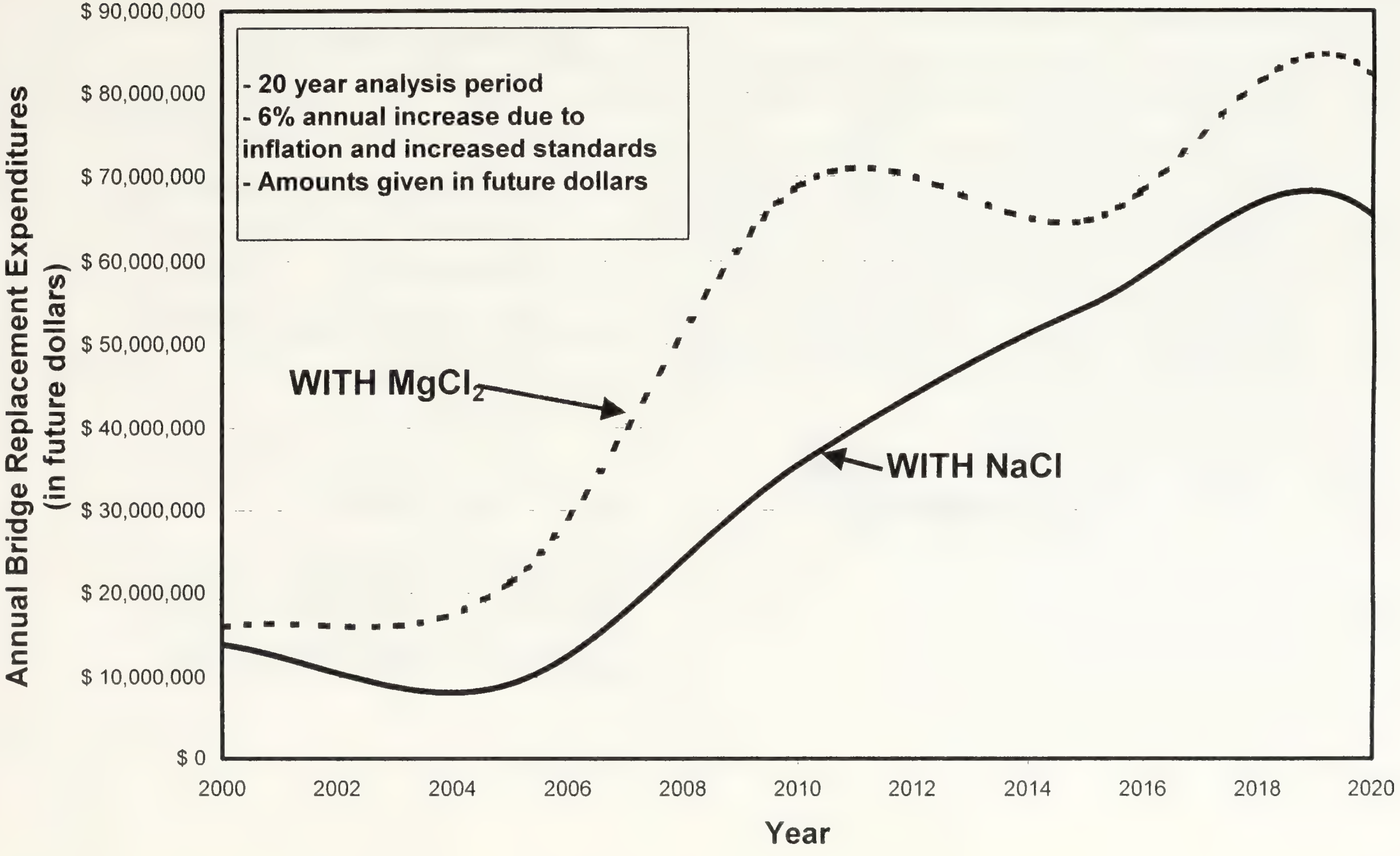
DIFFERENCE BETWEEN ANNUITIES = $11,600,000

DIFFERENCE IN THE SUM OF ALL EXPENDITURES IN YEAR 2000 DOLLARS = $289,000,000

Difference in Annual Bridge Replacement Needs If Entire System Treated with $MgCl_2$ vs NaCl Assuming $MgCl_2$ Reduces Service Life by 25%



Future Annual Bridge Replacement Needs Entire System Treated Assuming $MgCl_2$ Reduces Service Life by 25%



- 20 year analysis period
- 6% annual increase due to inflation and increased standards
- Amounts given in future dollars

Future Replacement Needs of all Currently Treated Bridges
($MgCl_2$ decreases remaining life by 30%)
Future dollars with 6% increase for inflation & increased standards

Assumptions:

-2% = Value of Money; difference between bank interest rate and inflation rate
2000 = Current Year (for analysis purposes) (this is equal to 6% inflation and increased standards)
20 = Analysis Period (years)

	Expenditure Year	2000	2005	2010	2015
Option 1	Expenditure Description	Bridge Replacements	Bridge Replacements	Bridge Replacements	Bridge Replacements
With $MgCl_2$	Expenditure (Current $)	$ 89,237,700	$ 106,563,600	$ 295,008,350	$ 275,261,700
	Present Worth	$ 89,237,700	$ 117,890,417	$ 361,055,156	$ 372,695,932
Option 2	Expenditure Description	Bridge Replacements	Bridge Replacements	Bridge Replacements	Bridge Replacements
Without $MgCl_2$	Expenditure (Current $)	$ 69,867,100	$ 41,582,850	$ 144,870,100	$ 201,055,650
	Present Worth	$ 69,867,100	$ 46,002,758	$ 177,303,783	$ 272,223,207

	Sum of Present Worths	**Annuity**
Option 1	**$ 940,879,206**	**$ 37,795,037**
Option 2	**$ 565,396,849**	**$ 22,711,943**
Difference	**$ 375,482,356**	**$ 15,083,094**

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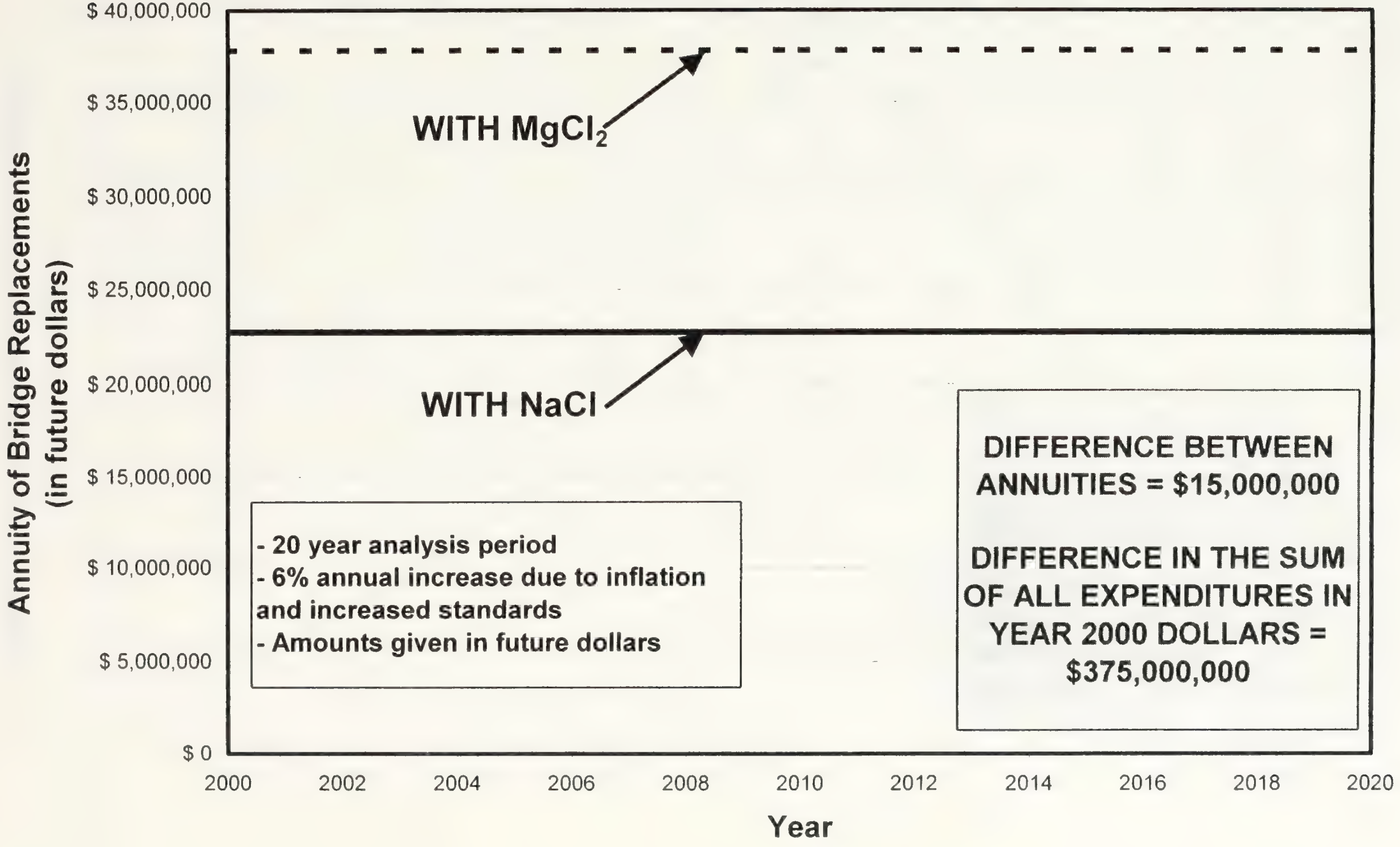
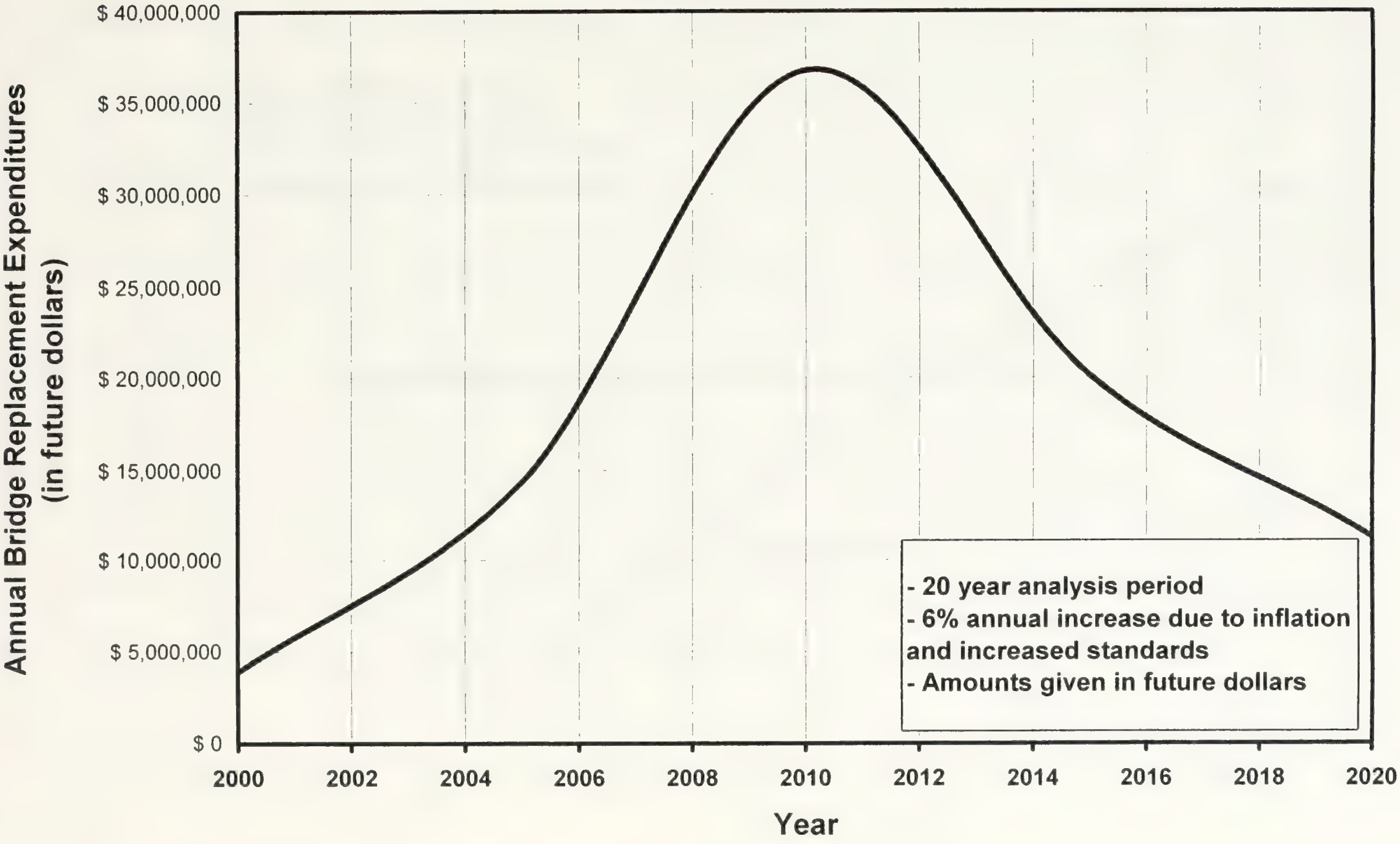


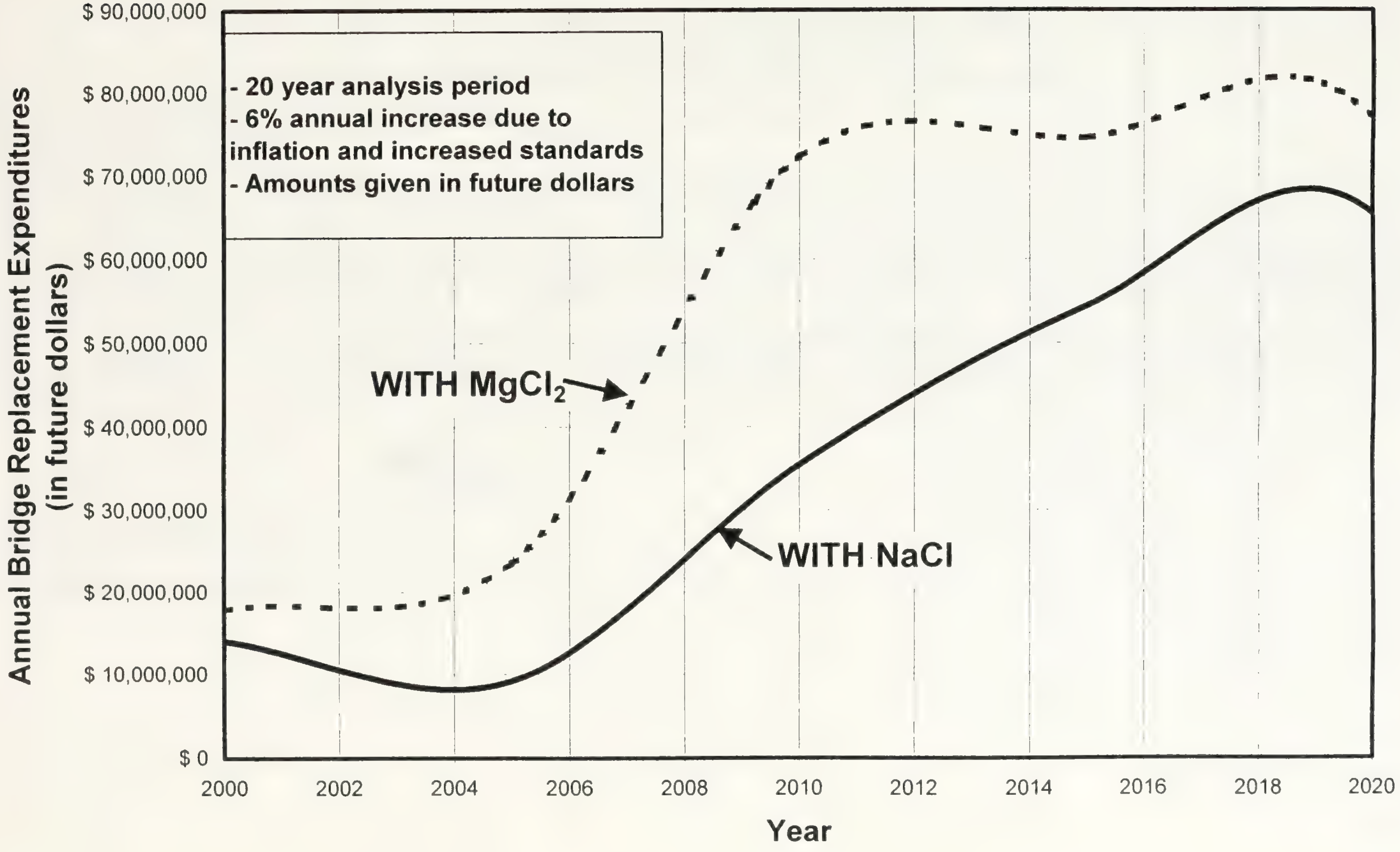
Future Average Bridge Replacement Needs for all Currently Treated Bridges

Assuming $MgCl_2$ Reduces Service Life by 30%

Difference in Annual Bridge Replacement Needs If Entire System Treated with $MgCl_2$ vs NaCl Assuming $MgCl_2$ Reduces Service Life by 30%



Future Annual Bridge Replacement Needs Entire System Treated Assuming $MgCl_2$ Reduces Service Life by 30%



Present Worth Analysis:
Future Replacement Needs of all Currently Treated Bridges
($MgCl_2$ decreases remaining life by 20%)
Future dollars with 6% increase for inflation & increased standards

Assumptions:

-2% = Value of Money; difference between bank interest rate and inflation rate (this is equal to 6% inflation and increased standards)
2000 = Current Year (for analysis purposes)
60 = Analysis Period (years)

	Expenditure Year	2000	2005	2010	2015	2020	2025	2030	2035	2040	2045	2050	2055
Option 1	Expenditure Description	Bridge Replacements	Bridge Replacements	Bridge Replacements	Bridge Replacements	Bridge Replacements	Bridge Replacements	Bridge Replacements	Bridge Replacements	Bridge Replacements	Bridge Replacements	Bridge Replacements	Bridge Replacements
With $MgCl_2$	Expenditure (Current $)	$ 80,053,800	$ 67,255,450	$ 269,722,150	$ 258,867,300	$ 198,074,850	$ 181,777,050	$ 74,605,100	$ 59,967,900	$ 32,580,650	$ 98,818,350	$ 308,441,500	$ 216,274,750
	Present Worth	$ 80,053,800	$ 74,404,141	$ 330,107,853	$ 350,498,415	$ 296,693,357	$ 301,222,327	$ 136,768,551	$ 121,620,334	$ 73,099,889	$ 245,281,160	$ 846,971,939	$ 657,009,510
Option 2	Expenditure Description	Bridge Replacements	Bridge Replacements	Bridge Replacements	Bridge Replacements	Bridge Replacements	Bridge Replacements	Bridge Replacements	Bridge Replacements	Bridge Replacements	Bridge Replacements	Bridge Replacements	Bridge Replacements
Without $MgCl_2$	Expenditure (Current $)	$ 69,867,100	$ 41,582,850	$ 144,870,100	$ 201,055,650	$ 218,523,000	$ 163,186,150	$ 182,999,500	$ 84,430,700	$ 30,102,400	$ 55,251,750	$ 28,051,950	$ 57,390,750
	Present Worth	$ 69,867,100	$ 46,002,758	$ 177,303,783	$ 272,223,207	$ 327,322,335	$ 270,415,390	$ 335,480,771	$ 171,233,108	$ 67,539,539	$ 137,142,680	$ 77,029,889	$ 174,344,294

	Sum of Present Worths	Annuity
Option 1	$ 3,513,731,275	$ 29,767,997
Option 2	$ 2,125,904,855	$ 18,010,463
Difference	$ 1,387,826,420	$ 11,757,533

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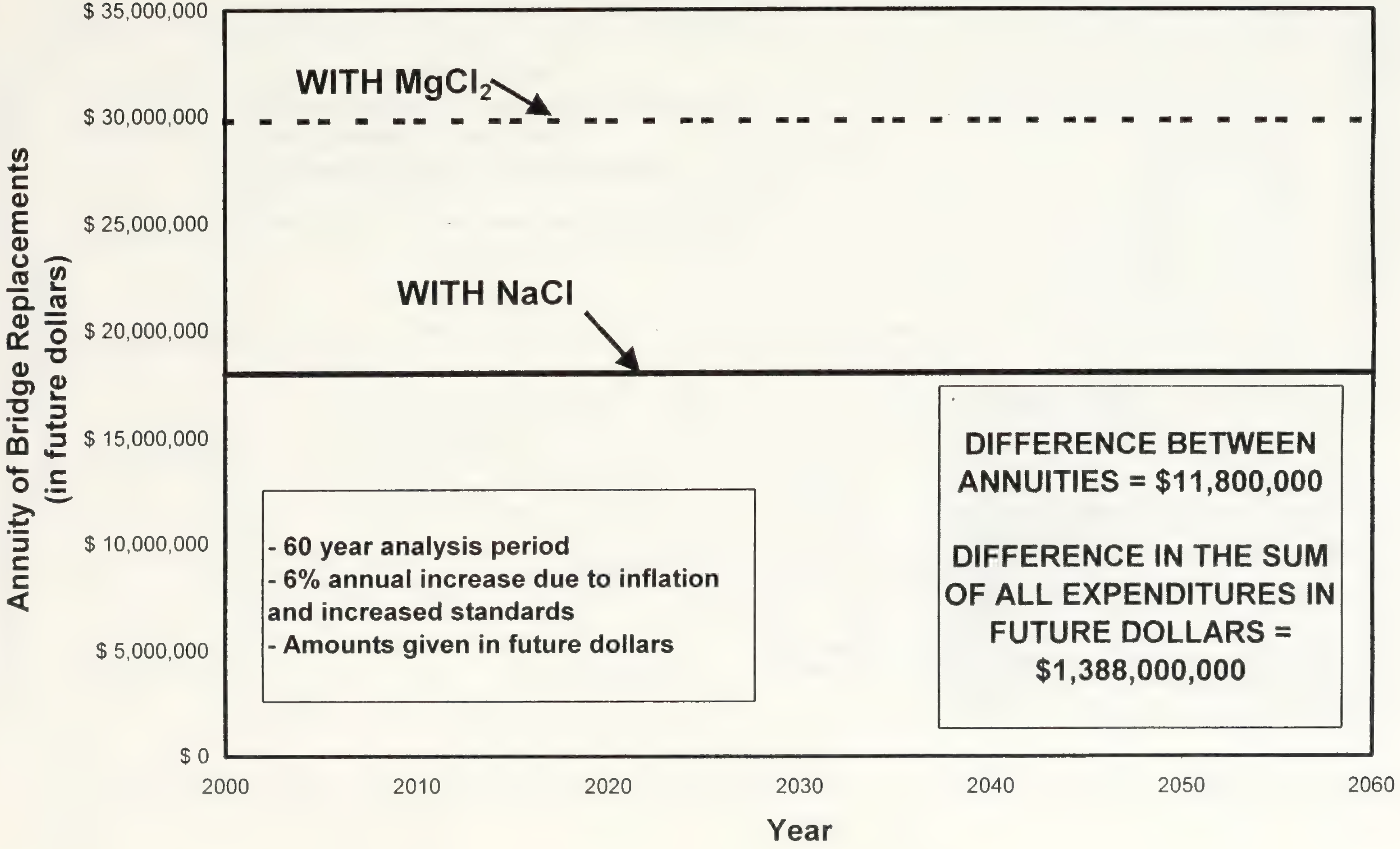
Future Average Bridge Replacement Needs for all Currently Treated Bridges

Assuming $MgCl_2$ Reduces Service Life by 20%

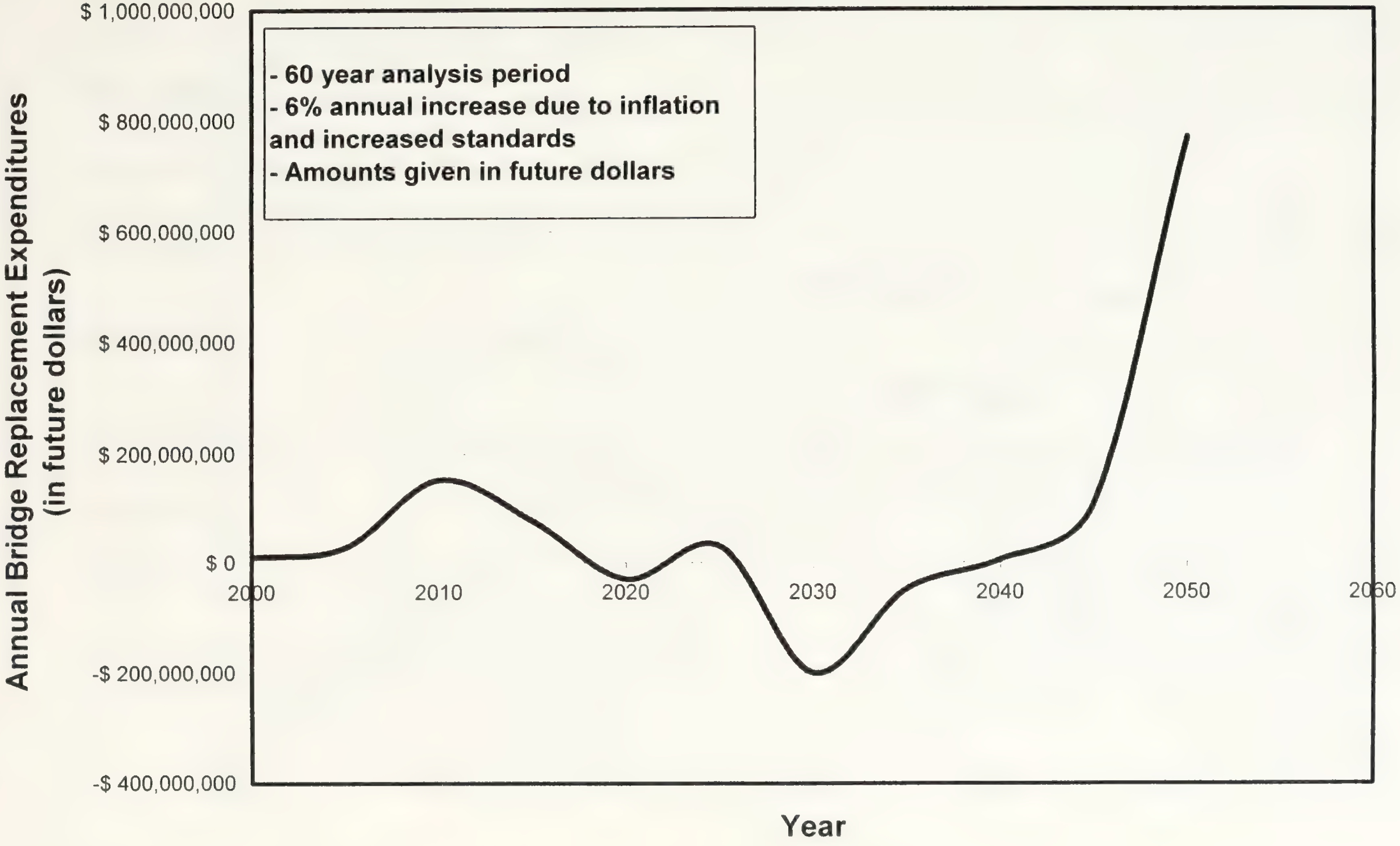


- 60 year analysis period
- 6% annual increase due to inflation and increased standards
- Amounts given in future dollars

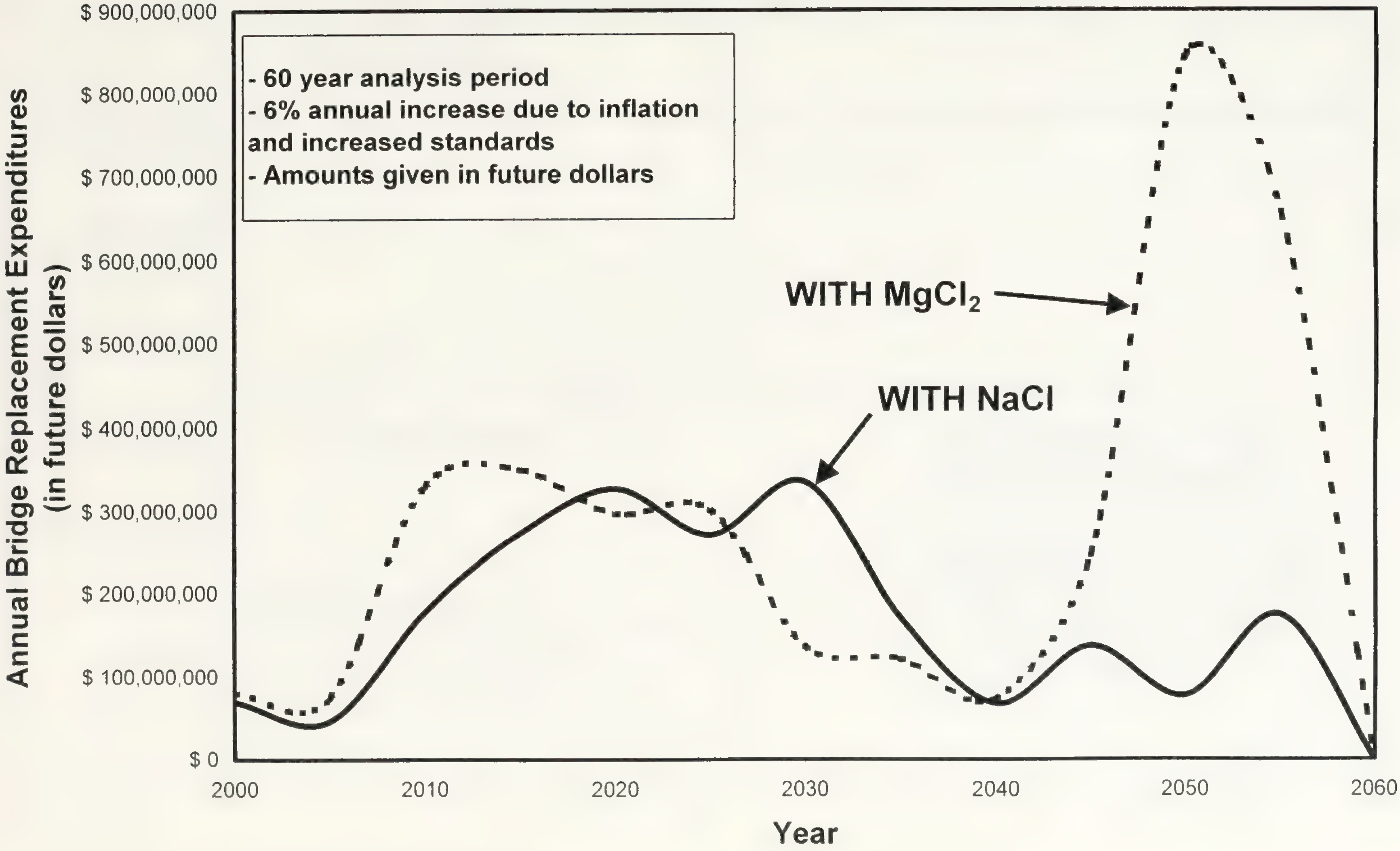
DIFFERENCE BETWEEN ANNUITIES = $11,800,000

DIFFERENCE IN THE SUM OF ALL EXPENDITURES IN FUTURE DOLLARS = $1,388,000,000

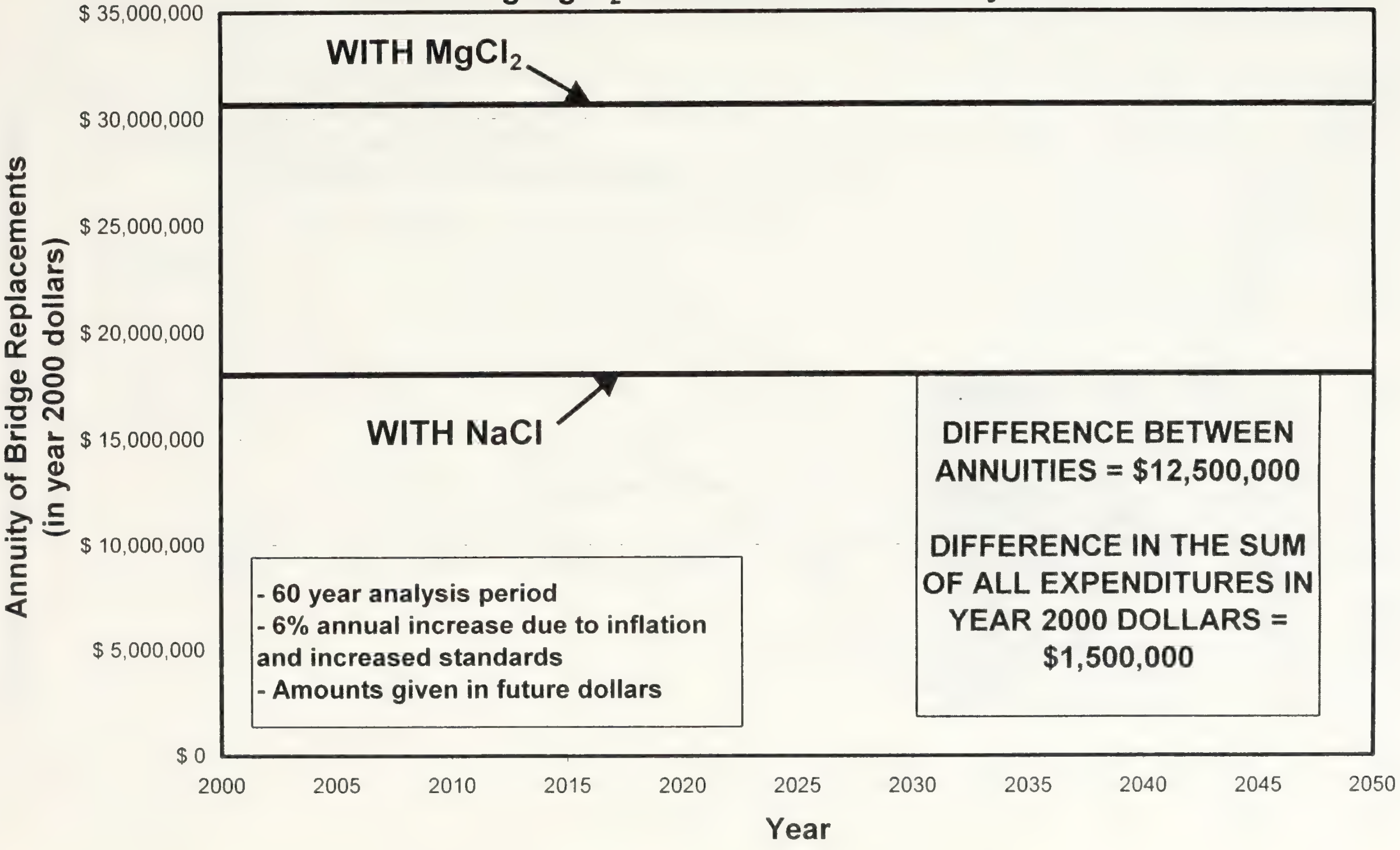
Difference in Annual Bridge Replacement Needs If Entire System Treated with $MgCl_2$ vs NaCl Assuming $MgCl_2$ Reduces Service Life by 20%



Future Annual Bridge Replacement Needs Entire System Treated Assuming $MgCl_2$ Reduces Service Life by 20%

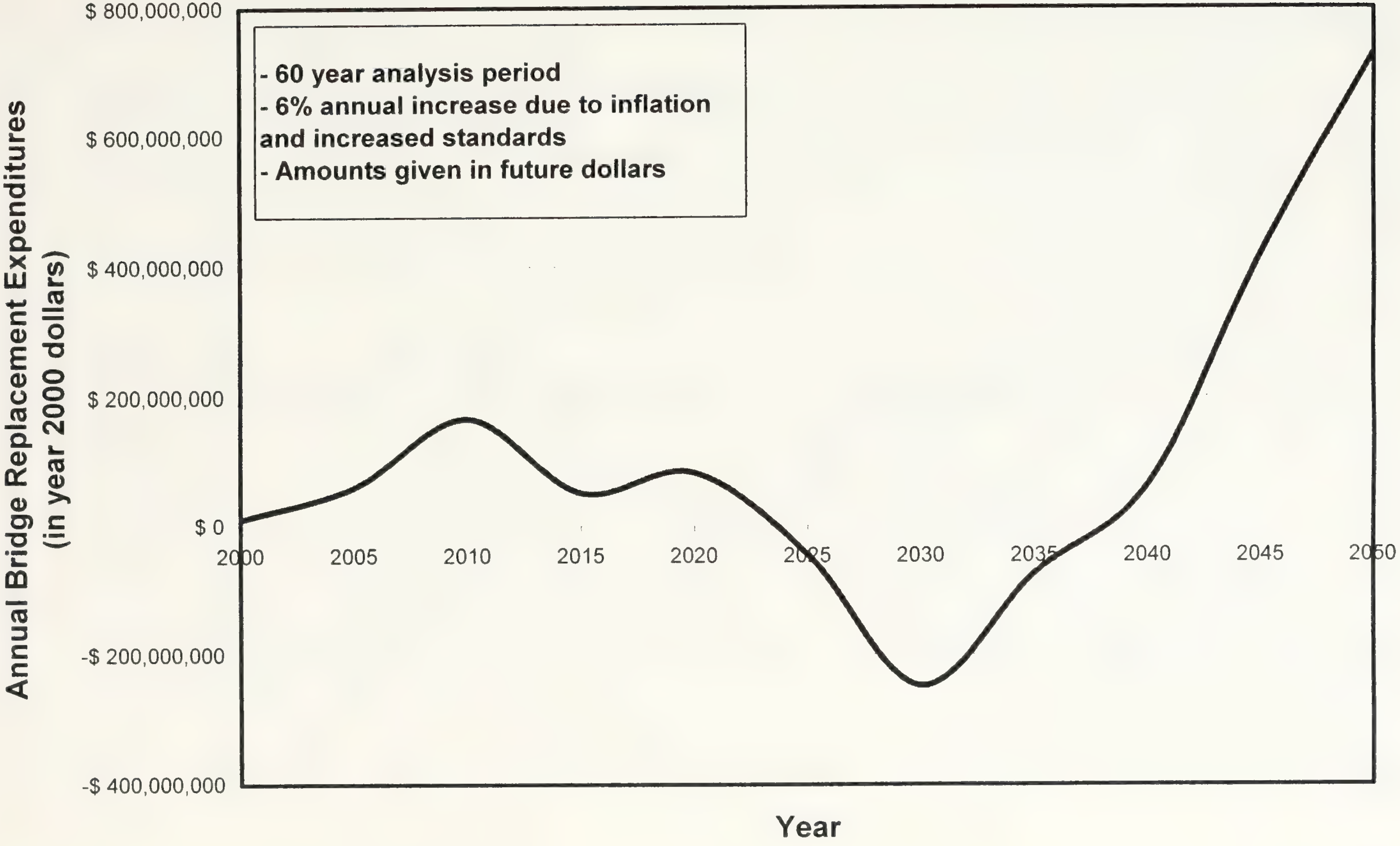


- 60 year analysis period
- 6% annual increase due to inflation and increased standards
- Amounts given in future dollars

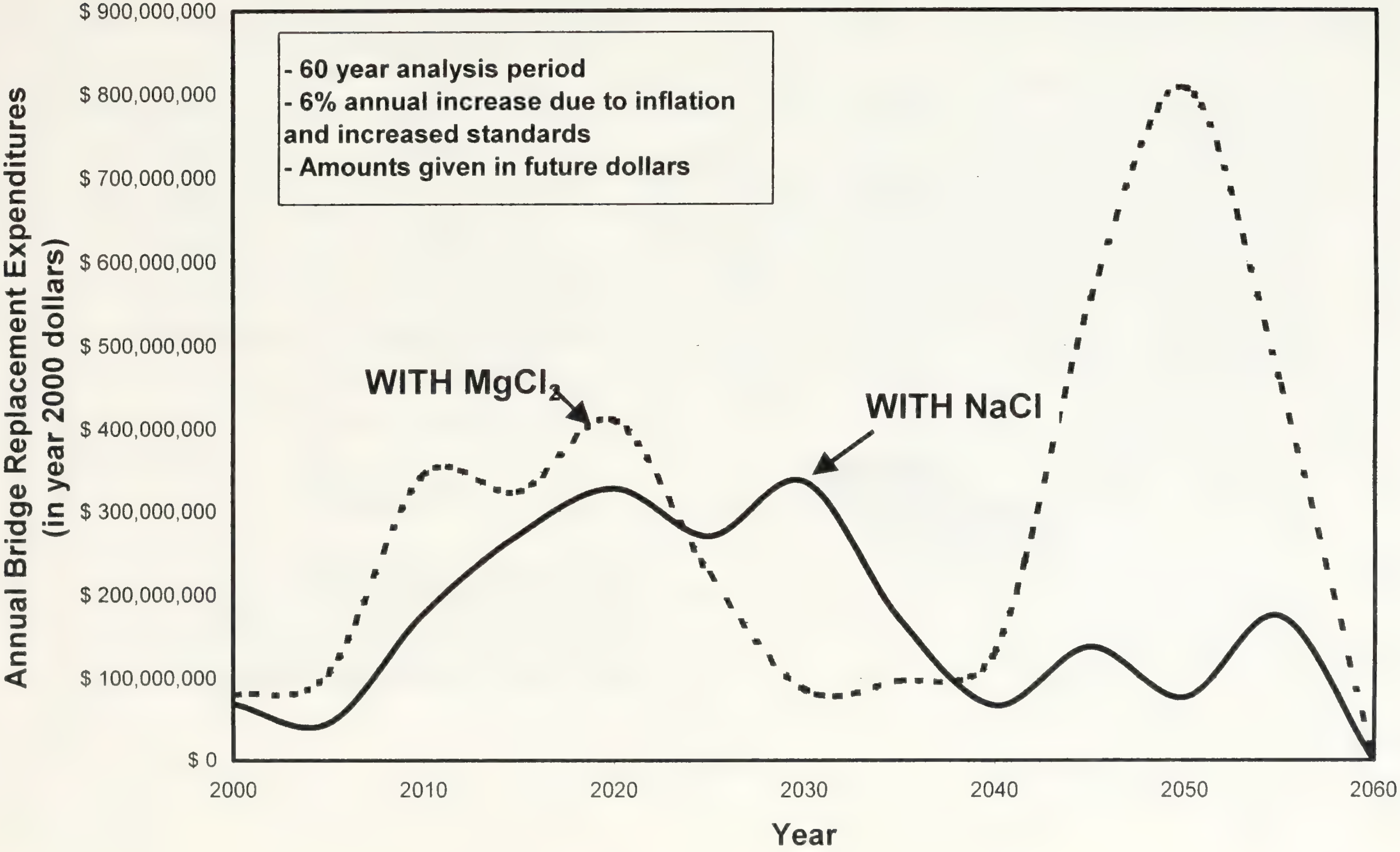


Future Average Bridge Replacement Needs for all Currently Treated Bridges
Assuming $MgCl_2$ Reduces Service Life by 25%

Difference in Annual Bridge Replacement Needs If Entire System Treated with $MgCl_2$ vs NaCl Assuming $MgCl_2$ Reduces Service Life by 25%



Future Annual Bridge Replacement Needs Entire System Treated Assuming $MgCl_2$ Reduces Service Life by 25%



Present Worth Analysis:
Future Replacement Needs of Currently $MgCl_2$ Treated Bridges
($MgCl_2$ decreases remaining life by 20%)

Assumptions:

4% = Value of Money (difference between bank interest rate and inflation rate)
2000 = Current Year (for analysis purposes)
20 = Analysis Period (years)

	Expenditure Year	2000	2005	2010	2015
Option 1	Expenditure Description	Bridge Replacements	Bridge Replacements	Bridge Replacements	Bridge Replacements
With $MgCl_2$	Expenditure (Current $)	$ 13,310,100	$ 18,388,500	$ 90,042,700	$ 33,116,550
	Present Worth	$ 13,310,100	$ 15,114,007	$ 60,829,622	$ 18,388,445
Option 2	Expenditure Description	Bridge Replacements	Bridge Replacements	Bridge Replacements	Bridge Replacements
Without $MgCl_2$	Expenditure (Current $)	$ 11,509,200	$ 4,474,650	$ 51,894,900	$ 55,887,700
	Present Worth	$ 11,509,200	$ 3,677,836	$ 35,058,335	$ 31,032,456

	Sum of Present Worths	**Annuity**
Option 1	**$ 107,642,173**	**$ 7,920,500**
Option 2	**$ 81,277,827**	**$ 5,980,565**

Difference	**$ 26,364,346**	**$ 1,939,935**

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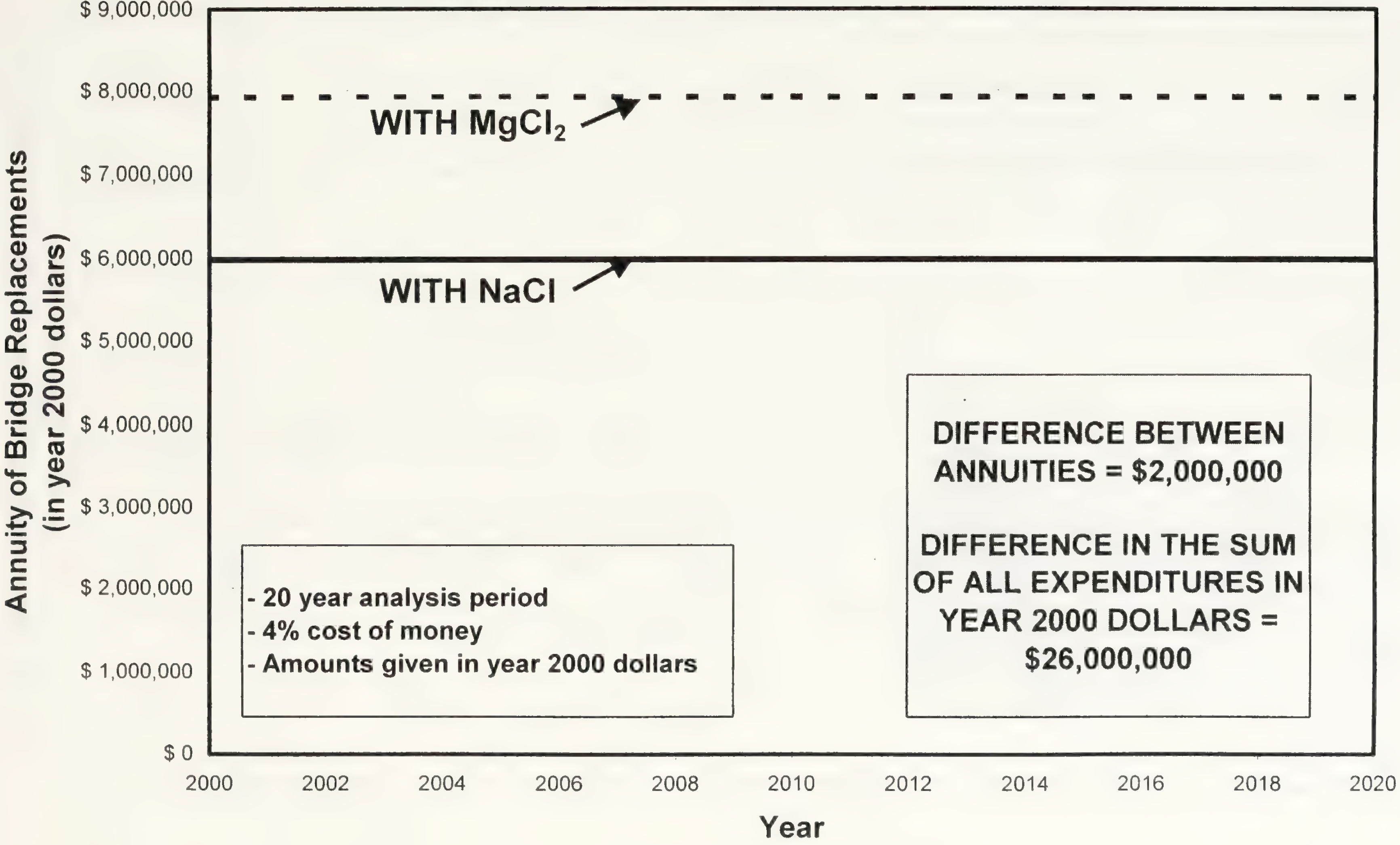
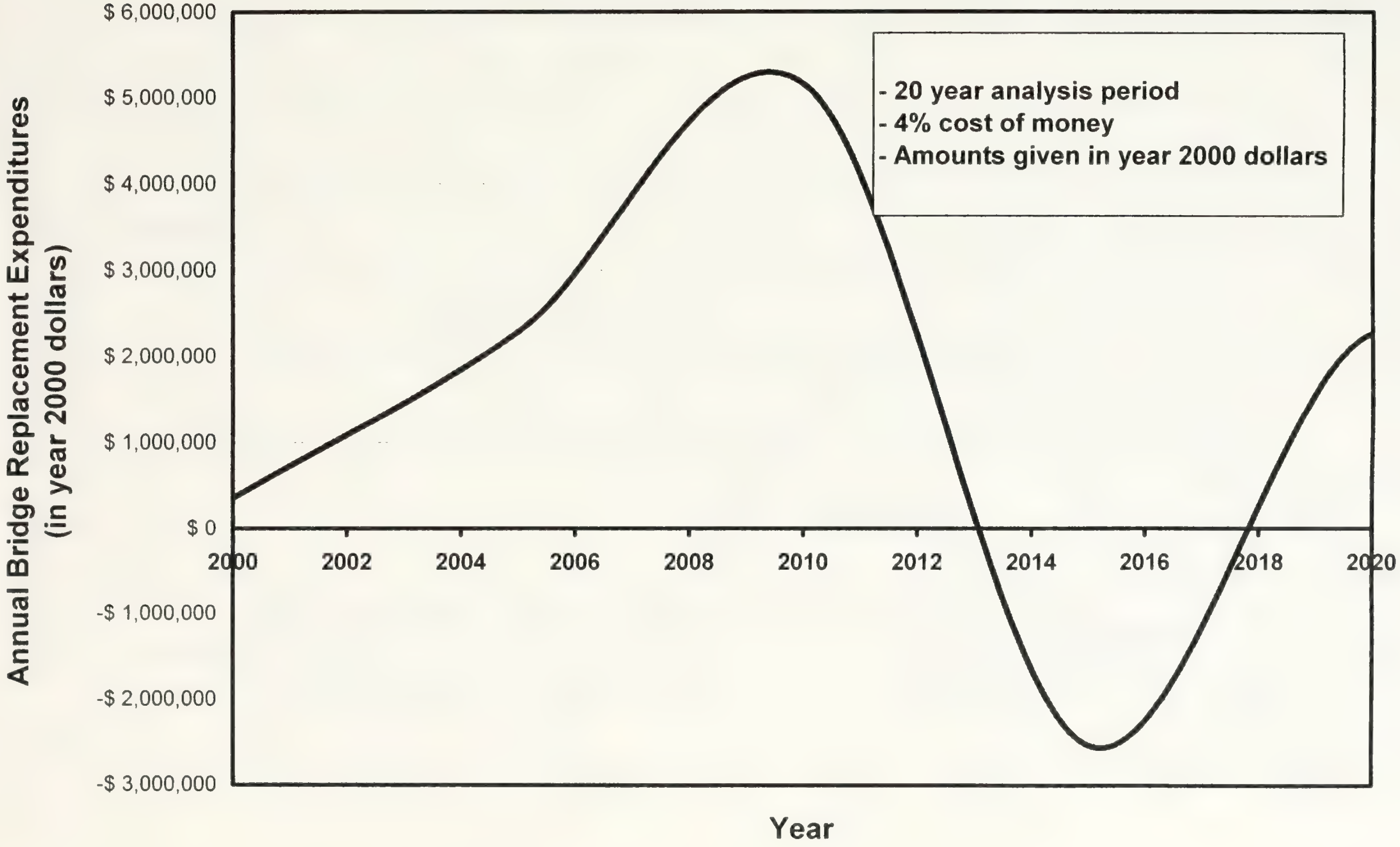
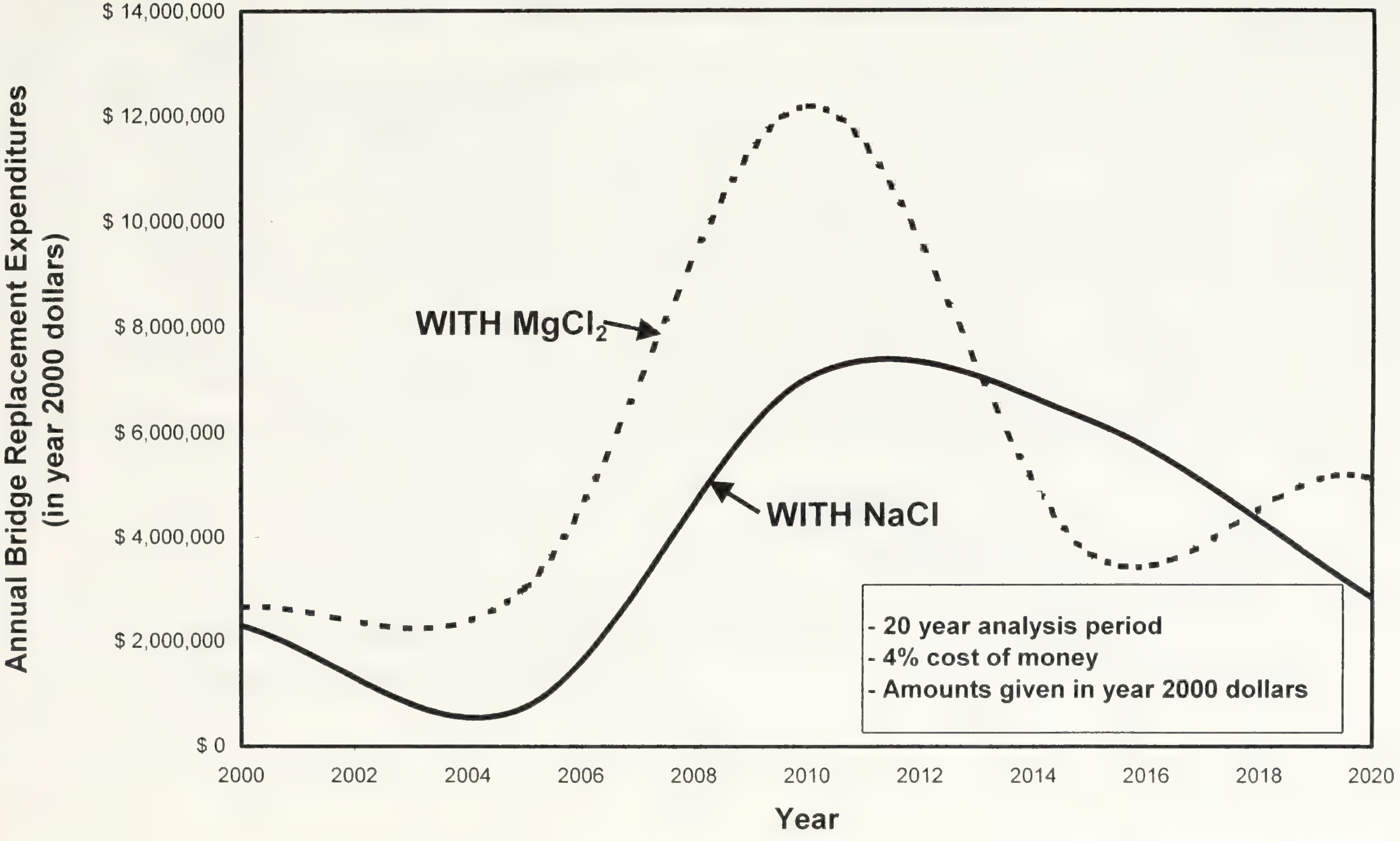


Future Average Bridge Replacement Needs for Current $MgCl_2$ Treated Bridges
Assuming $MgCl_2$ Reduces Service Life by 20%


Difference in Annual Bridge Replacement Needs If Partial System Treated with $MgCl_2$ vs NaCl Assuming $MgCl_2$ Reduces Service Life by 20%

Future Annual Bridge Replacement Needs If Partial System Treated Assuming $MgCl_2$ Reduces Service Life by 20%



- 20 year analysis period
- 4% cost of money
- Amounts given in year 2000 dollars

Present Worth Analysis:
Future Replacement Needs of Currently $MgCl_2$ Treated Bridges
($MgCl_2$ decreases remaining life by 25%)

Assumptions:

4% = Value of Money (difference between bank interest rate and inflation rate)
2000 = Current Year (for analysis purposes)
20 = Analysis Period (years)

	Expenditure Year	2000	2005	2010	2015
Option 1 With $MgCl_2$	Expenditure Description	Bridge Replacements	Bridge Replacements	Bridge Replacements	Bridge Replacements
	Expenditure (Current $)	$ 13,310,100	$ 24,173,000	$ 86,283,350	$ 35,682,200
	Present Worth	$ 13,310,100	$ 19,868,444	$ 58,289,940	$ 19,813,059
Option 2 Without $MgCl_2$	Expenditure Description	Bridge Replacements	Bridge Replacements	Bridge Replacements	Bridge Replacements
	Expenditure (Current $)	$ 11,509,200	$ 4,474,650	$ 51,894,900	$ 55,887,700
	Present Worth	$ 11,509,200	$ 3,677,836	$ 35,058,335	$ 31,032,456

	Sum of Present Worths	**Annuity**
Option 1	**$ 111,281,543**	**$ 8,188,291**
Option 2	**$ 81,277,827**	**$ 5,980,565**
Difference	**$ 30,003,716**	**$ 2,207,726**

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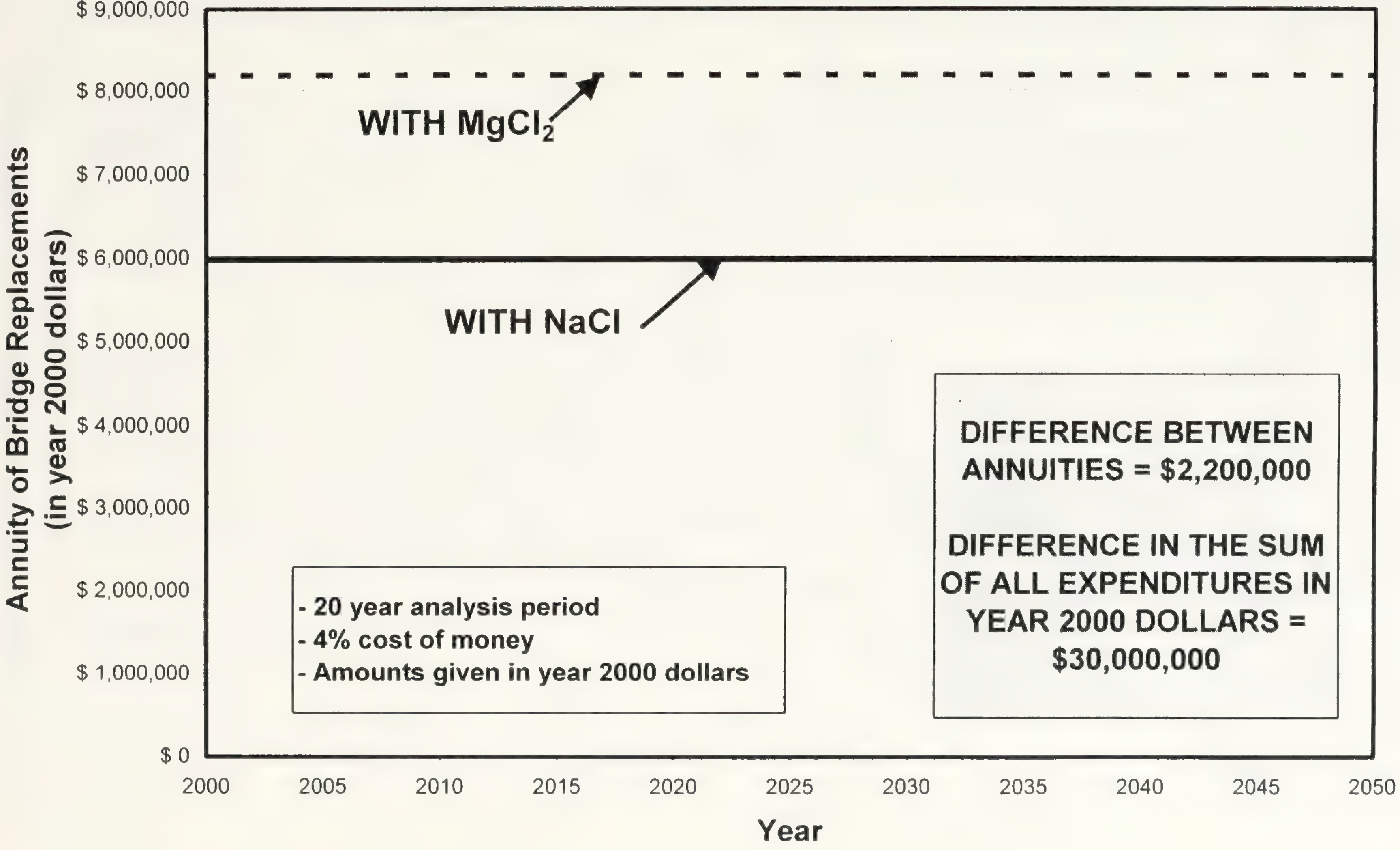
Future Average Bridge Replacement Needs for Current $MgCl_2$ Treated Bridges
Assuming $MgCl_2$ Reduces Service Life by 25%

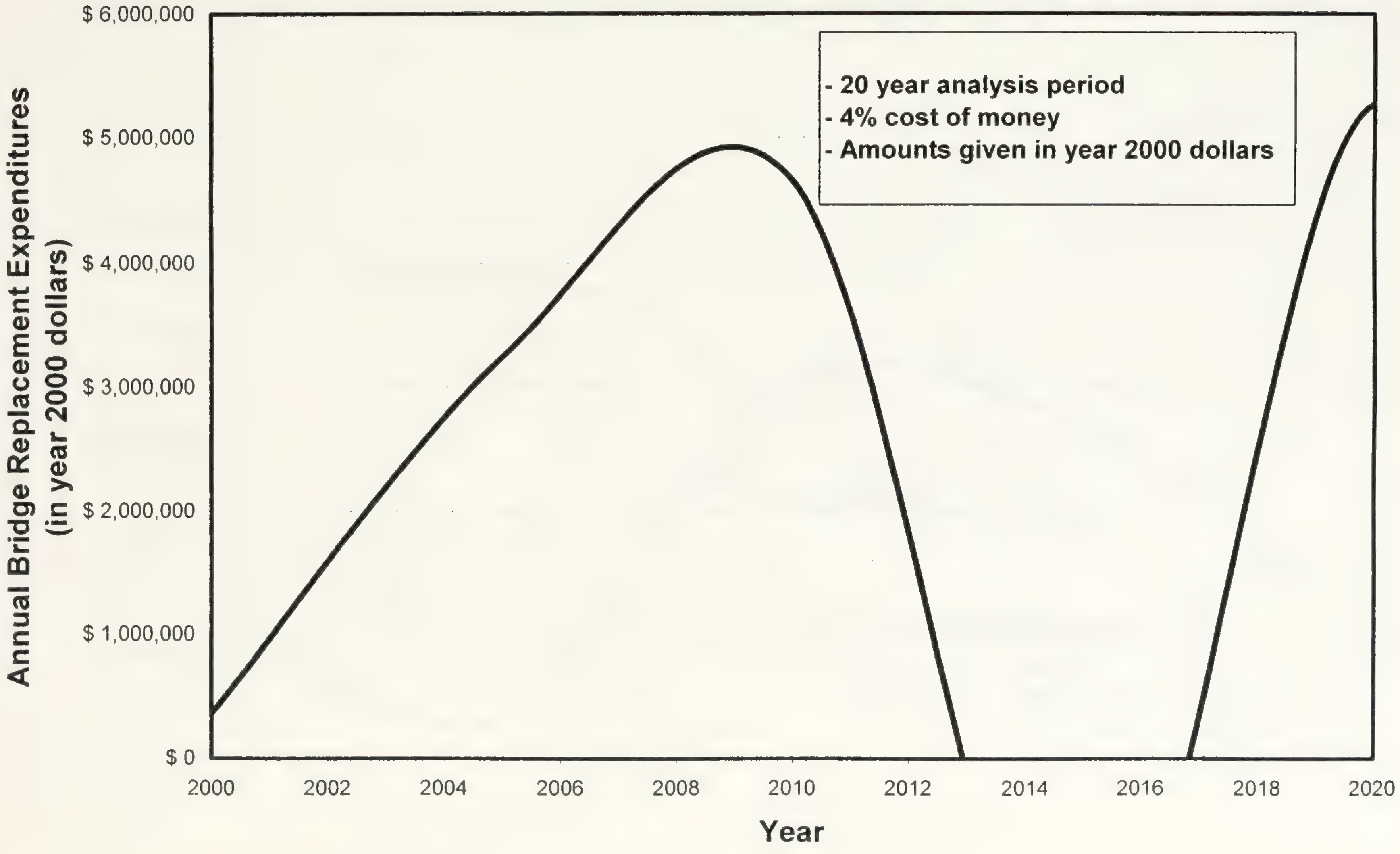


- 20 year analysis period
- 4% cost of money
- Amounts given in year 2000 dollars

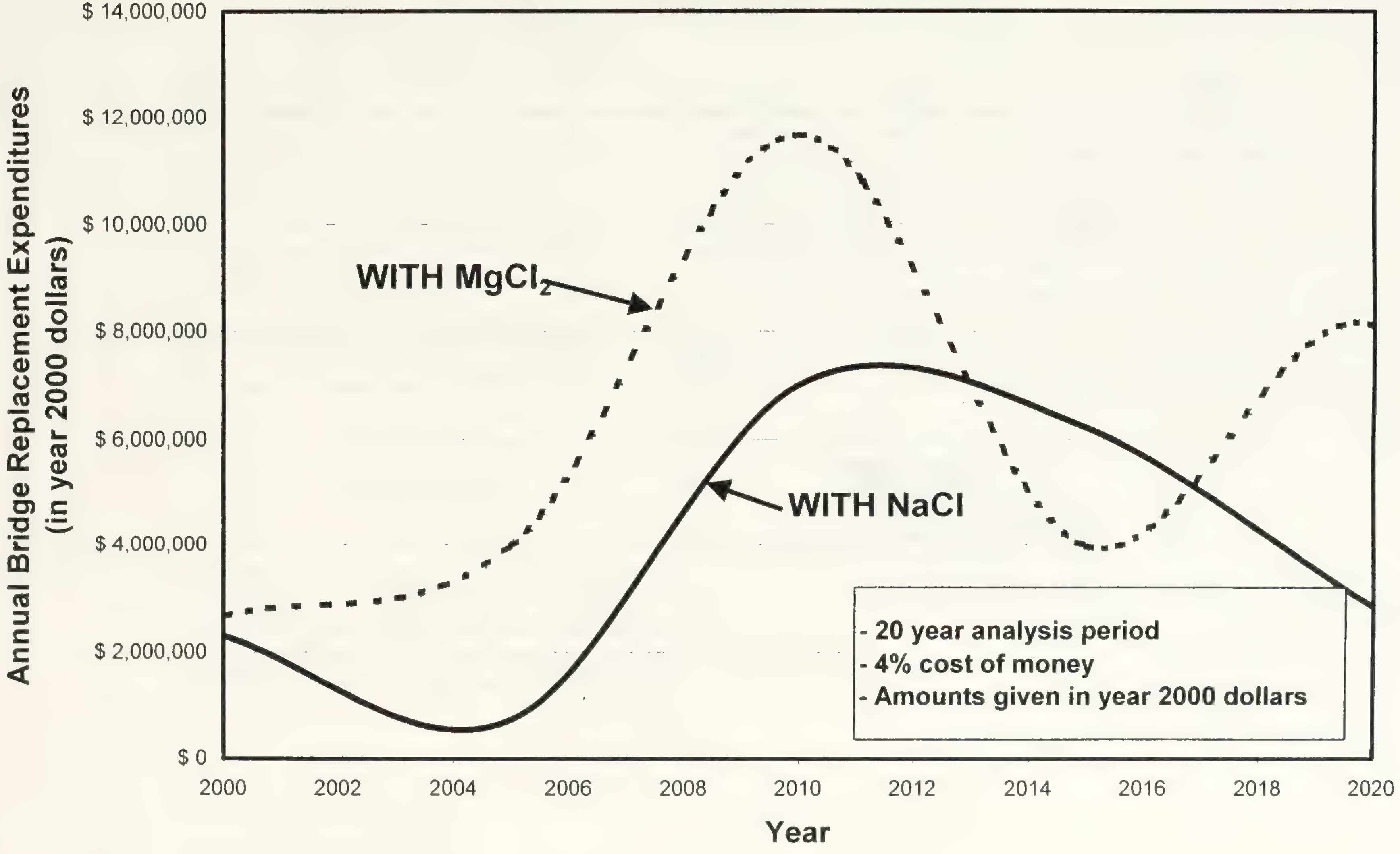
DIFFERENCE BETWEEN ANNUITIES = $2,200,000

DIFFERENCE IN THE SUM OF ALL EXPENDITURES IN YEAR 2000 DOLLARS = $30,000,000

Difference in Annual Bridge Replacement Needs If Partial System Treated with $MgCl_2$ vs NaCl Assuming $MgCl_2$ Reduces Service Life by 25%



Future Annual Bridge Replacement Needs If Partial System Treated Assuming $MgCl_2$ Reduces Service Life by 25%



Present Worth Analysis:
Future Replacement Needs of Currently $MgCl_2$ Treated Bridges
($MgCl_2$ decreases remaining life by 30%)

Assumptions:

4% = Value of Money (difference between bank interest rate and inflation rate)
2000 = Current Year (for analysis purposes)
20 = Analysis Period (years)

	Expenditure Year	2000	2005	2010	2015
Option 1	Expenditure Description	Bridge Replacements	Bridge Replacements	Bridge Replacements	Bridge Replacements
With $MgCl_2$	Expenditure (Current $)	$ 13,310,100	$ 26,407,450	$ 85,808,400	$ 52,353,750
	Present Worth	$ 13,310,100	$ 21,704,999	$ 57,969,080	$ 29,070,179
Option 2	Expenditure Description	Bridge Replacements	Bridge Replacements	Bridge Replacements	Bridge Replacements
Without $MgCl_2$	Expenditure (Current $)	$ 11,509,200	$ 4,474,650	$ 51,894,900	$ 55,887,700
	Present Worth	$ 11,509,200	$ 3,677,836	$ 35,058,335	$ 31,032,456

	Sum of Present Worths	**Annuity**
Option 1	**$ 122,054,358**	**$ 8,980,973**
Option 2	**$ 81,277,827**	**$ 5,980,565**
Difference	**$ 40,776,531**	**$ 3,000,409**

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Present Worth Analysis:
Future Replacement Needs of all Currently Treated Bridges
($MgCl_2$ decreases remaining life by 25%, 6% inflation)

Assumptions:

-2% = Value of Money; difference between bank interest rate and inflation rate (this is equal to 6% inflation and increased standards)
2000 = Current Year (for analysis purposes)
60 = Analysis Period (years)

	Expenditure Year	2000	2005	2010	2015	2020	2025	2030	2035	2040	2045	2050	2055
Option 1	Expenditure Description	Bridge Replacements	Bridge Replacements	Bridge Replacements	Bridge Replacements	Bridge Replacements	Bridge Replacements	Bridge Replacements	Bridge Replacements	Bridge Replacements	Bridge Replacements	Bridge Replacements	Bridge Replacements
With $MgCl_2$	Expenditure (Current $)	$ 80,053,800	$ 96,119,300	$ 281,202,600	$ 239,099,950	$ 274,063,400	$ 135,897,800	$ 47,368,500	$ 47,707,750	$ 58,127,900	$ 224,147,650	$ 293,665,150	$ 148,519,050
	Present Worth	$ 80,053,800	$ 106,335,976	$ 344,158,559	$ 323,734,027	$ 410,515,470	$ 225,195,928	$ 86,837,510	$ 96,755,639	$ 130,419,222	$ 556,366,259	$ 806,396,485	$ 451,178,088
Option 2	Expenditure Description	Bridge Replacements	Bridge Replacements	Bridge Replacements	Bridge Replacements	Bridge Replacements	Bridge Replacements	Bridge Replacements	Bridge Replacements	Bridge Replacements	Bridge Replacements	Bridge Replacements	Bridge Replacements
Without $MgCl_2$	Expenditure (Current $)	$ 69,867,100	$ 41,582,850	$ 144,870,100	$ 201,055,650	$ 218,523,000	$ 163,186,150	$ 182,999,500	$ 84,430,700	$ 30,102,400	$ 55,251,750	$ 28,051,950	$ 57,390,750
	Present Worth	$ 69,867,100	$ 46,002,758	$ 177,303,783	$ 272,223,207	$ 327,322,335	$ 270,415,390	$ 335,480,771	$ 171,233,108	$ 67,539,539	$ 137,142,680	$ 77,029,889	$ 174,344,294

	Sum of Present Worths	Annuity
Option 1	$ 3,617,946,963	$ 30,650,902
Option 2	$ 2,125,904,855	$ 18,010,463

Difference	$ 1,492,042,108	$ 12,640,439

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Present Worth Analysis:
Future Replacement Needs of all Currently Treated Bridges
($MgCl_2$ decreases remaining life by 30%, 6% inflation)

Assumptions:

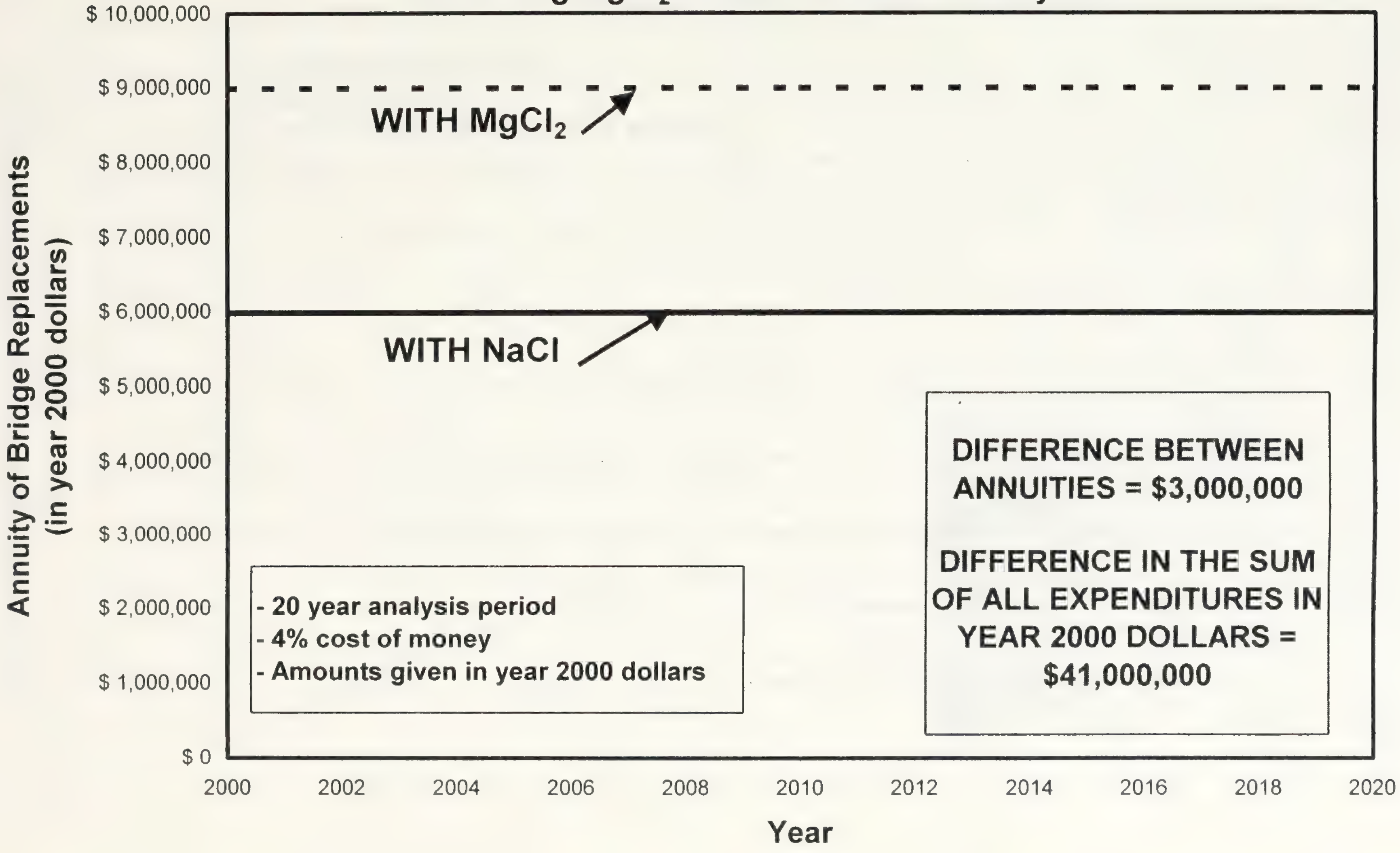
-2% = Value of Money; difference between bank interest rate and inflation rate (this is equal to 6% inflation and increased standards)
2000 = Current Year (for analysis purposes)
60 = Analysis Period (years)

	Expenditure Year	2000	2005	2010	2015	2020	2025	2030	2035	2040	2045	2050	2055
Option 1	Expenditure Description	Bridge Replacements	Bridge Replacements	Bridge Replacements	Bridge Replacements	Bridge Replacements	Bridge Replacements	Bridge Replacements	Bridge Replacements	Bridge Replacements	Bridge Replacements	Bridge Replacements	Bridge Replacements
With $MgCl_2$	Expenditure (Current $)	$ 89,237,700	$ 106,563,600	$ 295,008,350	$ 275,261,700	$ 256,013,000	$ 103,556,350	$ 64,682,900	$ 34,625,350	$ 149,664,450	$ 316,712,300	$ 204,980,600	$ 206,928,700
	Present Worth	$ 89,237,700	$ 117,890,417	$ 361,055,156	$ 372,695,932	$ 383,478,045	$ 171,602,987	$ 118,578,844	$ 70,223,347	$ 335,796,083	$ 786,124,848	$ 562,871,132	$ 628,617,644
Option 2	Expenditure Description	Bridge Replacements	Bridge Replacements	Bridge Replacements	Bridge Replacements	Bridge Replacements	Bridge Replacements	Bridge Replacements	Bridge Replacements	Bridge Replacements	Bridge Replacements	Bridge Replacements	Bridge Replacements
Without $MgCl_2$	Expenditure (Current $)	$ 69,867,100	$ 41,582,850	$ 144,870,100	$ 201,055,650	$ 218,523,000	$ 163,186,150	$ 182,999,500	$ 84,430,700	$ 30,102,400	$ 55,251,750	$ 28,051,950	$ 57,390,750
	Present Worth	$ 69,867,100	$ 46,002,758	$ 177,303,783	$ 272,223,207	$ 327,322,335	$ 270,415,390	$ 335,480,771	$ 171,233,108	$ 67,539,539	$ 137,142,680	$ 77,029,889	$ 174,344,294

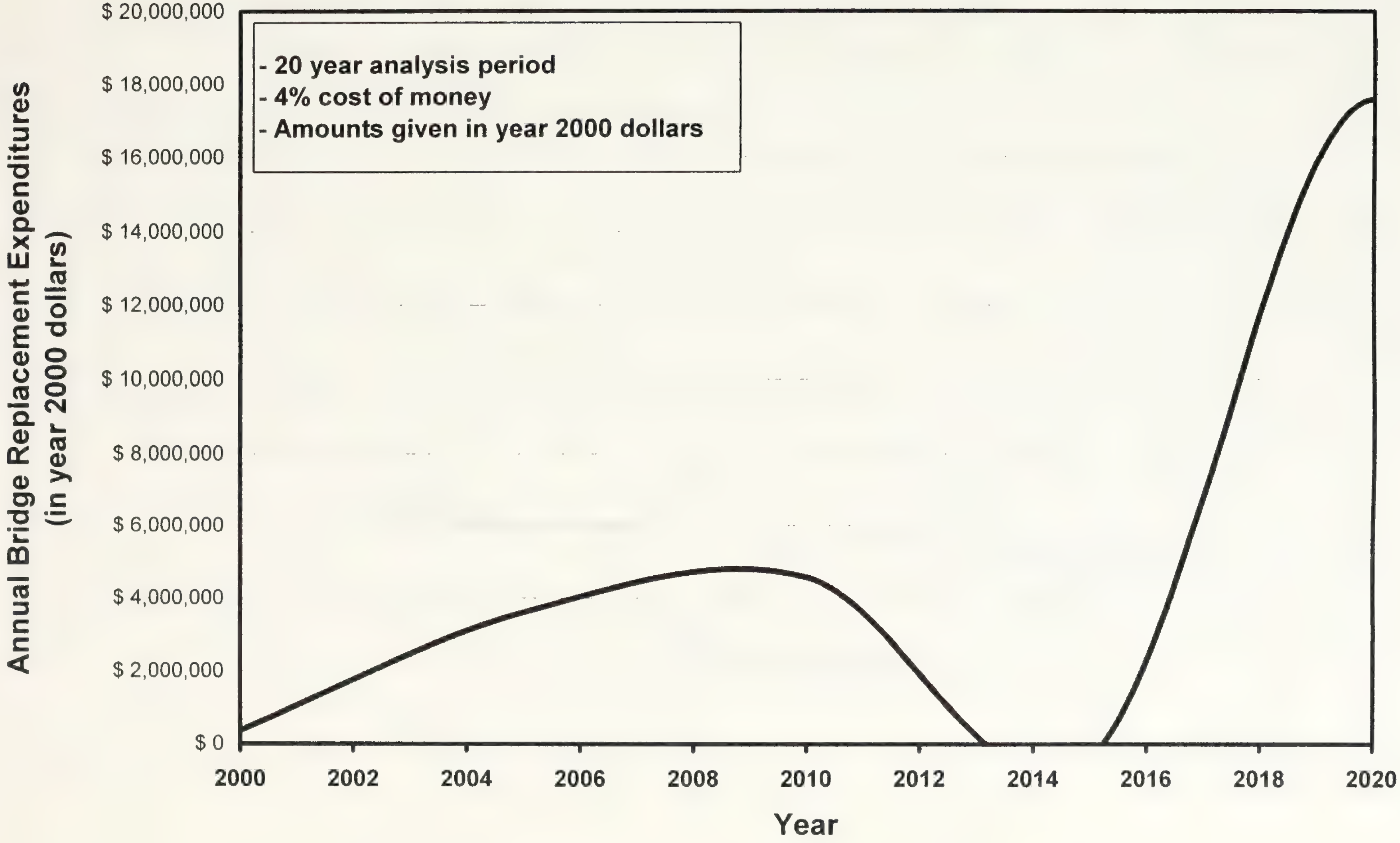
	Sum of Present Worths	Annuity
Option 1	$ 3,998,172,135	$ 33,872,133
Option 2	$ 2,125,904,855	$ 18,010,463

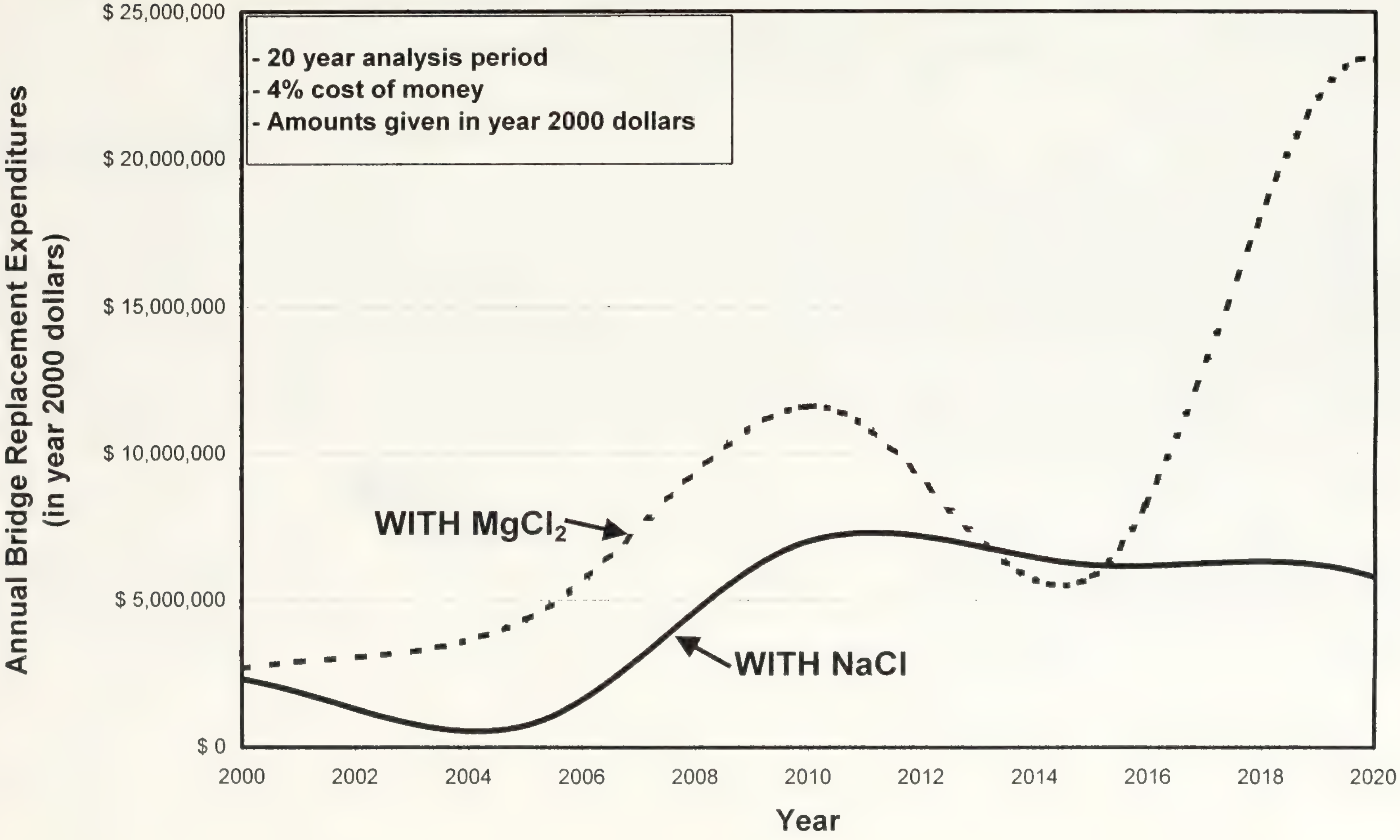
Difference	$ 1,872,267,281	$ 15,861,670

Future Average Bridge Replacement Needs for Current $MgCl_2$ Treated Bridges Assuming $MgCl_2$ Reduces Service Life by 30%



Difference in Annual Bridge Replacement Needs If Partial System Treated with $MgCl_2$ vs NaCl Assuming $MgCl_2$ Reduces Service Life by 30%





Future Annual Bridge Replacement Needs If Partial System Treated Assuming $MgCl_2$ Reduces Service Life by 30%

Present Worth Analysis:
Future Replacement Needs of Currently $MgCl_2$ Treated Bridges
($MgCl_2$ decreases remaining life by 20%)

Assumptions:

4% = Value of Money (difference between bank interest rate and inflation rate)
2000 = Current Year (for analysis purposes)
60 = Analysis Period (years)

	Expenditure Year	2000	2005	2010	2015	2020	2025	2030	2035	2040	2045	2050	2055
Option 1	Expenditure Description	Bridge Replacements	Bridge Replacements	Bridge Replacements	Bridge Replacements	Bridge Replacements	Bridge Replacements	Bridge Replacements	Bridge Replacements	Bridge Replacements	Bridge Replacements	Bridge Replacements	Bridge Replacements
With $MgCl_2$	Expenditure (Current $)	$ 13,310,100	$ 18,388 500	$ 90,042,700	$ 33,116 550	$ 55,918,750	$ 45,481,350	$ 14,933,900	$ 24,297,200	$ 7,669,350	$ 32,095,350	$ 93,484,650	$ 17,619,150
	Present Worth	$ 13,310,100	$ 15,114,007	$ 60,829,622	$ 18,388,445	$ 25,520,588	$ 17,060,819	$ 4,604,400	$ 6,157,286	$ 1,597,442	$ 5,494,673	$ 13,154,470	$ 2,037,752
Option 2	Expenditure Description	Bridge Replacements	Bridge Replacements	Bridge Replacements	Bridge Replacements	Bridge Replacements	Bridge Replacements	Bridge Replacements	Bridge Replacements	Bridge Replacements	Bridge Replacements	Bridge Replacements	Bridge Replacements
Without $MgCl_2$	Expenditure (Current $)	$ 11,509,200	$ 4,474,650	$ 51,894,900	$ 55,887,700	$ 31,091,400	$ 48,860,050	$ 51,273,900	$ 3,483,350	$ 13,857,500	$ 23,156,400	$ 6,303,150	$ 13,706,850
	Present Worth	$ 11,509,200	$ 3,677,836	$ 35,058,335	$ 31,032,456	$ 14,189,709	$ 18,328,226	$ 15,808,701	$ 882,735	$ 2,886,365	$ 3,964,339	$ 886,933	$ 1,585,273

	Sum of Present Worths	Annuity
Option 1	$ 183,269,602	$ 8,100,855
Option 2	$ 139,810,107	$ 6,179,865

Difference	$ 43,459,495	$ 1,920,990

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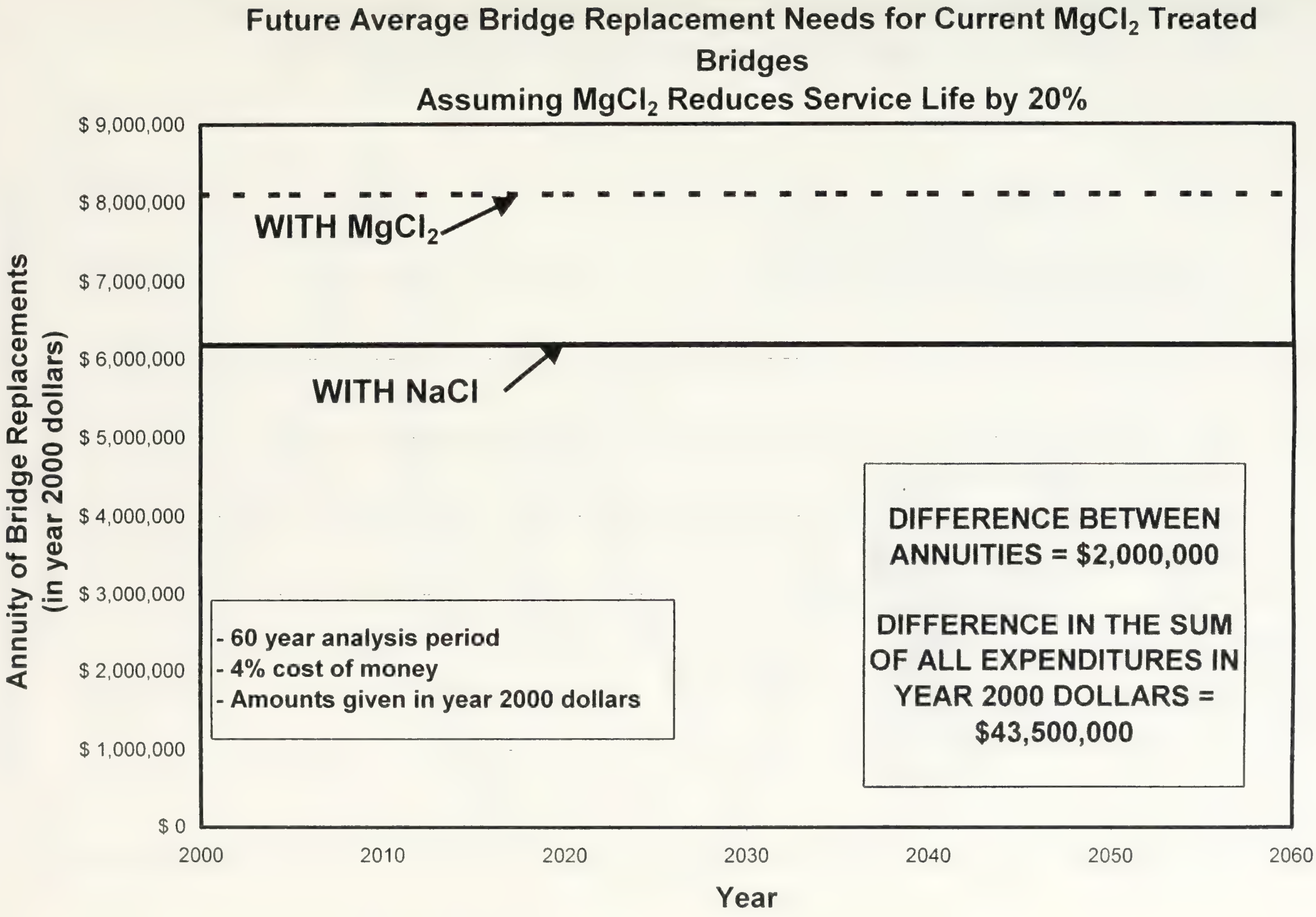
Annuity Chart
Pres Worth 60yr 20%-FINAL MgCl xls

Printed
03/14/2000



Future Average Bridge Replacement Needs for Current $MgCl_2$ Treated Bridges

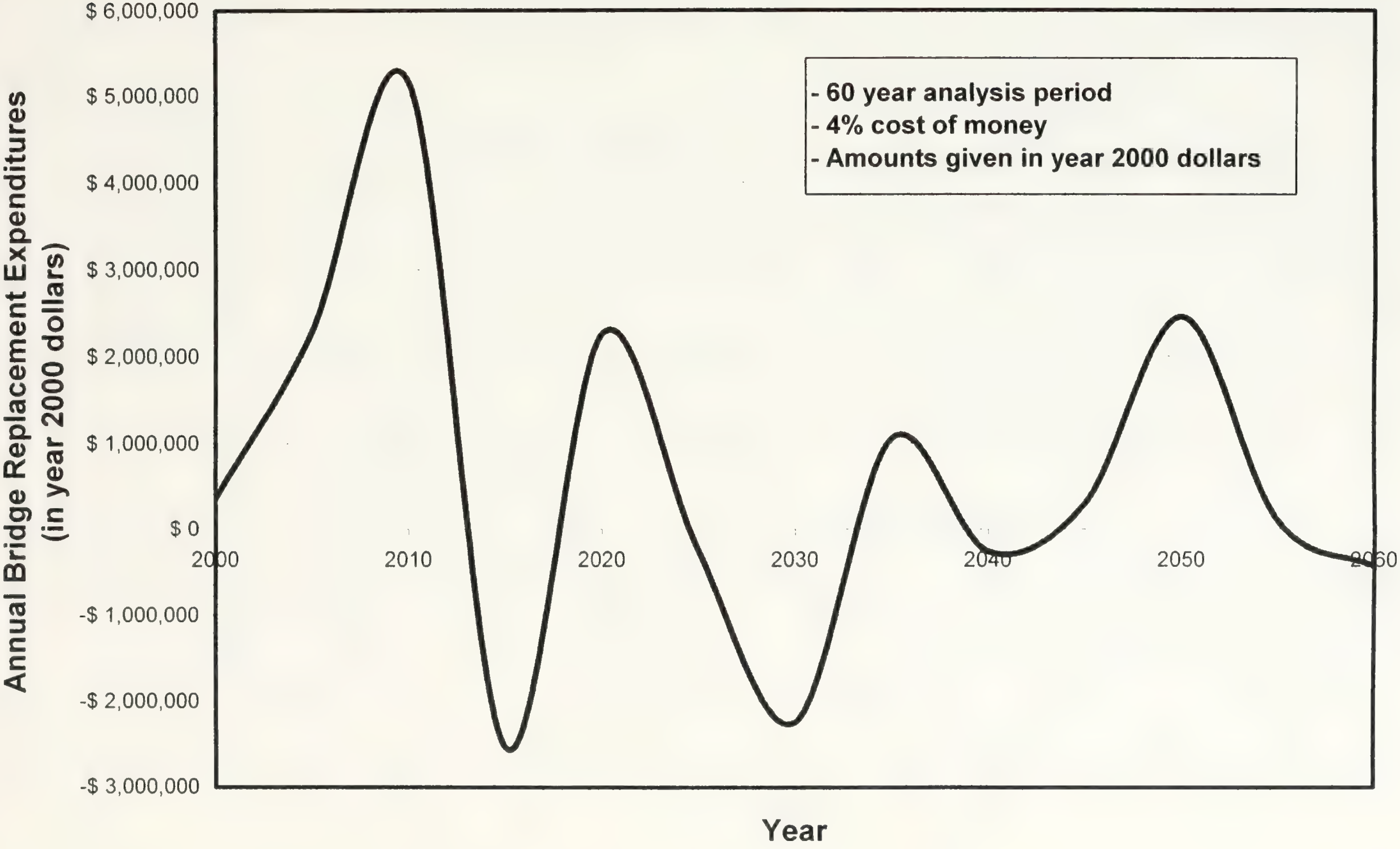
Assuming $MgCl_2$ Reduces Service Life by 20%

- 60 year analysis period
- 4% cost of money
- Amounts given in year 2000 dollars

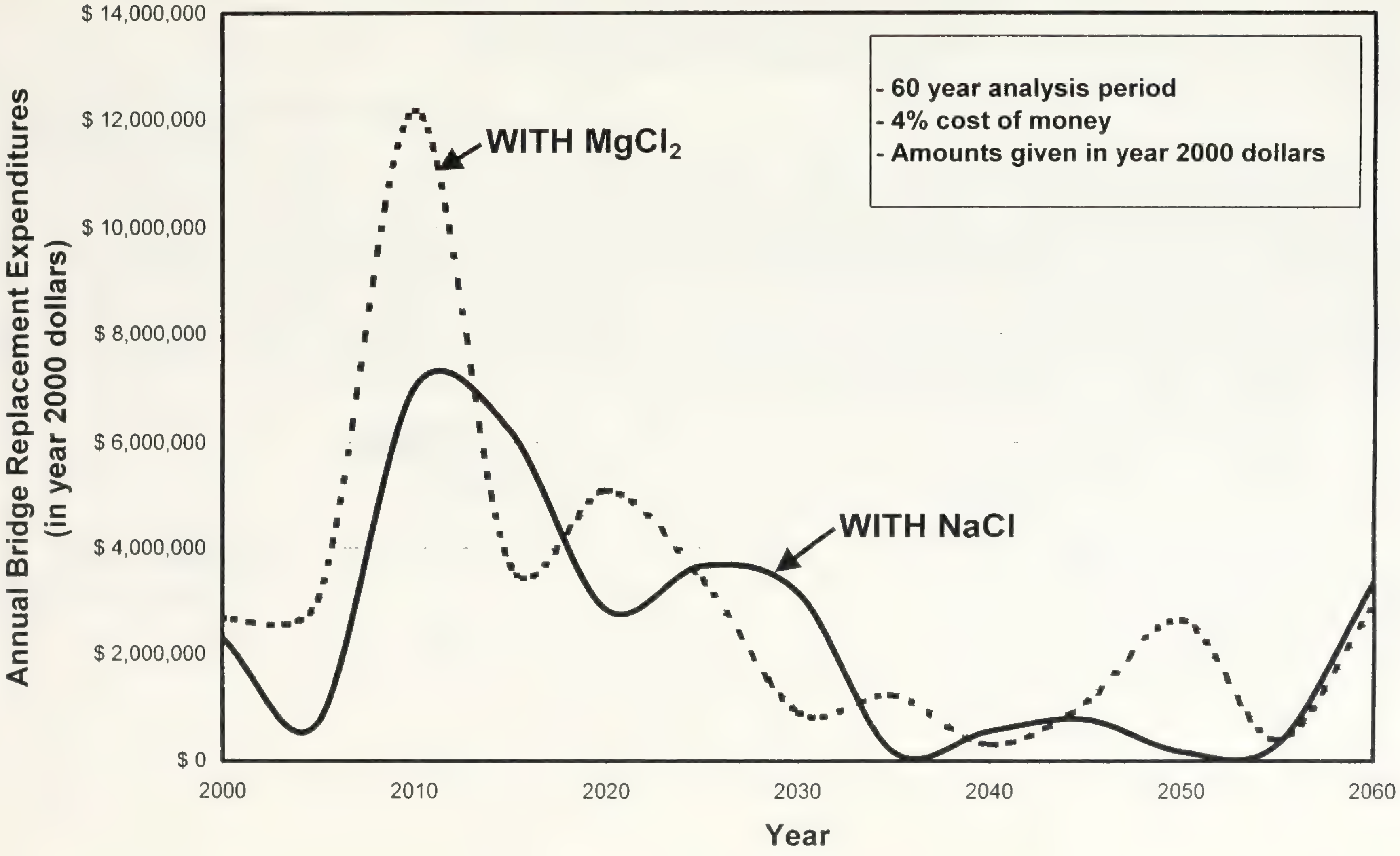
DIFFERENCE BETWEEN ANNUITIES = $2,000,000

DIFFERENCE IN THE SUM OF ALL EXPENDITURES IN YEAR 2000 DOLLARS = $43,500,000

Difference in Annual Bridge Replacement Needs If Partial System Treated with $MgCl_2$ vs NaCl Assuming $MgCl_2$ Reduces Service Life by 20%



Future Annual Bridge Replacement Needs If Partial System Treated Assuming $MgCl_2$ Reduces Service Life by 20%



Present Worth Analysis:
Future Replacement Needs of Currently $MgCl_2$ Treated Bridges
($MgCl_2$ decreases remaining life by 25%)

Assumptions:

4% = Value of Money (difference between bank interest rate and inflation rate)
2000 = Current Year (for analysis purposes)
60 = Analysis Period (years)

	Expenditure Year	2000	2005	2010	2015	2020	2025	2030	2035	2040	2045	2050	2055
Option 1	Expenditure Description	Bridge Replacements	Bridge Replacements	Bridge Replacements	Bridge Replacements	Bridge Replacements	Bridge Replacements	Bridge Replacements	Bridge Replacements	Bridge Replacements	Bridge Replacements	Bridge Replacements	Bridge Replacements
With $MgCl_2$	Expenditure (Current $)	$ 13,310,100	$ 24,173,000	$ 86,283,350	$ 35,682,200	$ 88,847,850	$ 10,178,650	$ 26,230,350	$ 16,560 000	$ 15,599,750	$ 67,482,000	$ 51,379,700	$ 21,829,300
	Present Worth	$ 13,310,100	$ 19,868,444	$ 58,289,940	$ 19,813,059	$ 40,548,999	$ 3,818,183	$ 8,087,307	$ 4,196,560	$ 3,249,257	$ 11,552,811	$ 7,229,772	$ 2,524,679
Option 2	Expenditure Description	Bridge Replacements	Bridge Replacements	Bridge Replacements	Bridge Replacements	Bridge Replacements	Bridge Replacements	Bridge Replacements	Bridge Replacements	Bridge Replacements	Bridge Replacements	Bridge Replacements	Bridge Replacements
Without $MgCl_2$	Expenditure (Current $)	$ 11,509,200	$ 4,474,650	$ 51,894,900	$ 55,887,700	$ 31,091,400	$ 48,860,050	$ 51,273,900	$ 3,483,350	$ 13,857,500	$ 23,156,400	$ 6,303,150	$ 13,706,850
	Present Worth	$ 11,509,200	$ 3,677,836	$ 35,058,335	$ 31,032,456	$ 14,189,709	$ 18,328,226	$ 15,808,701	$ 882,735	$ 2,886,365	$ 3,964,339	$ 886,933	$ 1,585,273

	Sum of Present Worths	Annuity
Option 1	$ 192,489,110	$ 8,508,374
Option 2	$ 139,810,107	$ 6,179,865

Difference	$ 52,679,003	$ 2,328,509

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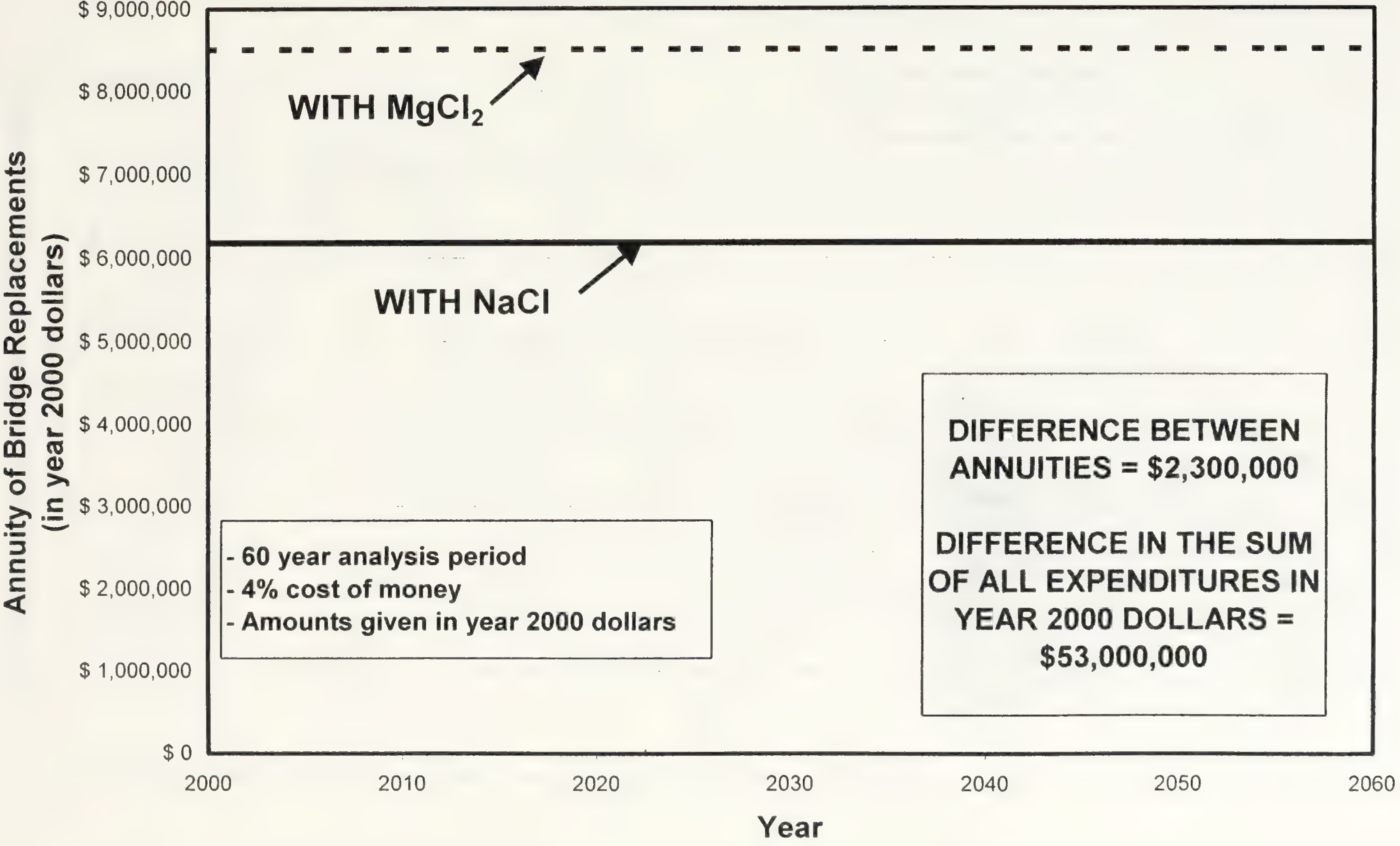
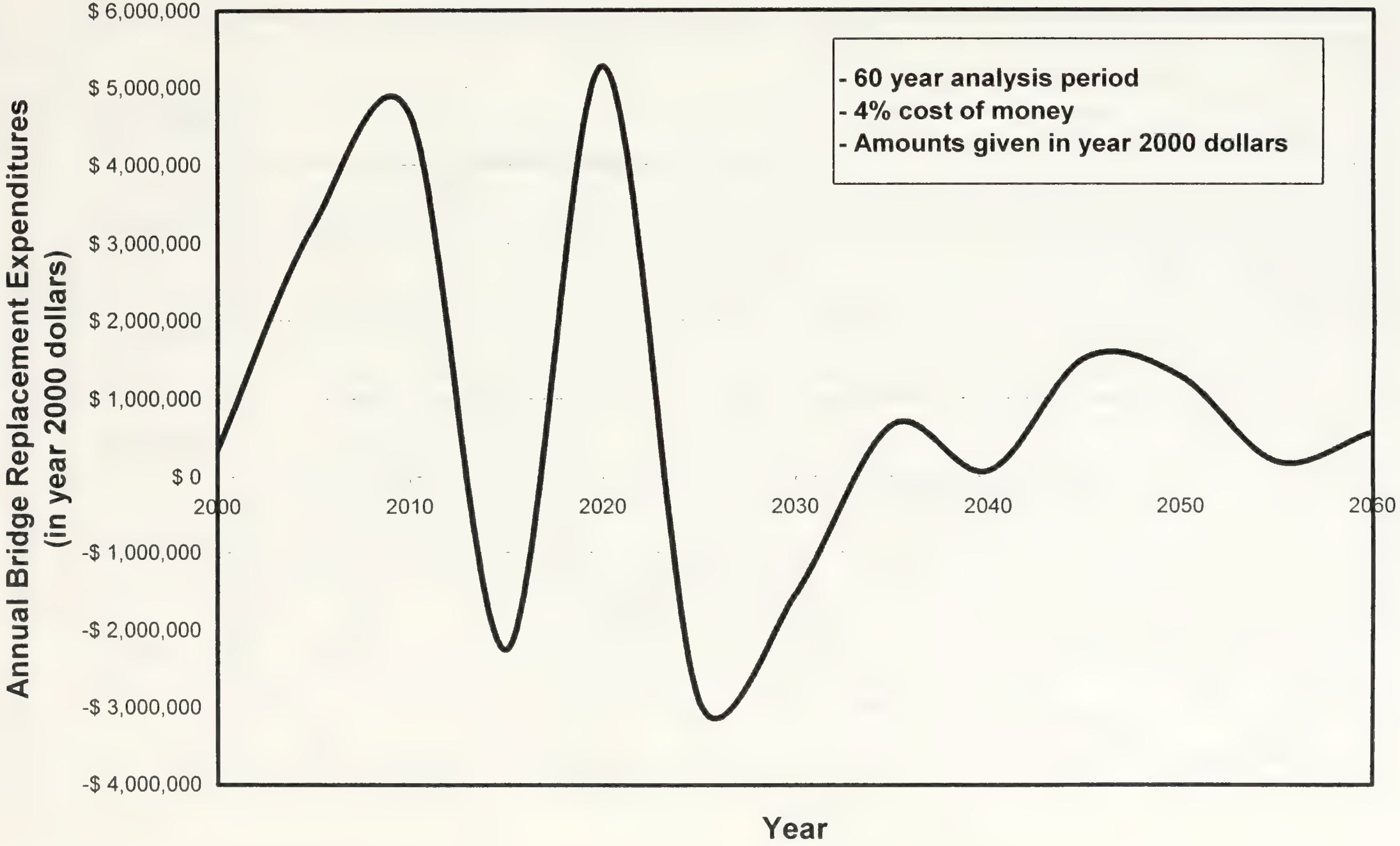


Future Average Bridge Replacement Needs for Current $MgCl_2$ Treated Bridges

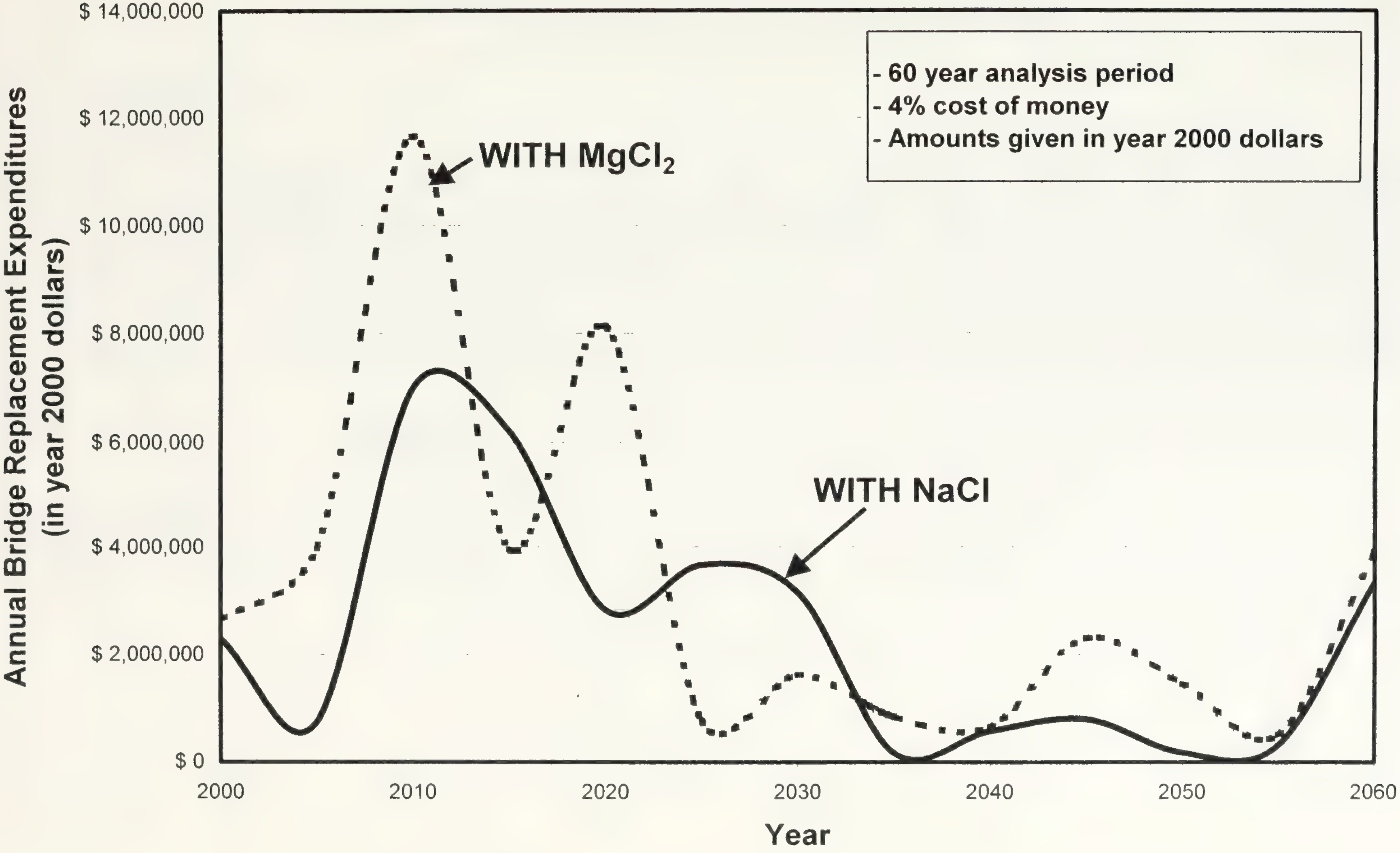
Assuming $MgCl_2$ Reduces Service Life by 25%

Difference in Annual Bridge Replacement Needs If Partial System Treated with $MgCl_2$ vs NaCl Assuming $MgCl_2$ Reduces Service Life by 25%



- 60 year analysis period
- 4% cost of money
- Amounts given in year 2000 dollars

Future Annual Bridge Replacement Needs If Partial System Treated Assuming $MgCl_2$ Reduces Service Life by 25%



- 60 year analysis period
- 4% cost of money
- Amounts given in year 2000 dollars

Present Worth Analysis:
Future Replacement Needs of Currently $MgCl_2$ Treated Bridges
($MgCl_2$ decreases remaining life by 30%)

Assumptions:

4% = Value of Money (difference between bank interest rate and inflation rate)
2000 = Current Year (for analysis purposes)
60 = Analysis Period (years)

	Expenditure Year	2000	2005	2010	2015	2020	2025	2030	2035	2040	2045	2050	2055
Option 1	Expenditure Description	Bridge Replacements	Bridge Replacements	Bridge Replacements	Bridge Replacements	Bridge Replacements	Bridge Replacements	Bridge Replacements	Bridge Replacements	Bridge Replacements	Bridge Replacements	Bridge Replacements	Bridge Replacements
With $MgCl_2$	Expenditure (Current $)	$ 13,310,100	$ 26,407,450	$ 85,808,400	$ 52,353,750	$ 77,112,100	$ 12,798,350	$ 27,698,900	$ 7,669,350	$ 40,114,300	$ 85,465,700	$ 25,346,000	$ 69,355,350
	Present Worth	$ 13,310,100	$ 21,704,999	$ 57,969,080	$ 29,070,179	$ 35,192,956	$ 4,800,876	$ 8,540,088	$ 1,943,532	$ 8,355,369	$ 14,631,592	$ 3,566,502	$ 8,021,329
Option 2	Expenditure Description	Bridge Replacements	Bridge Replacements	Bridge Replacements	Bridge Replacements	Bridge Replacements	Bridge Replacements	Bridge Replacements	Bridge Replacements	Bridge Replacements	Bridge Replacements	Bridge Replacements	Bridge Replacements
Without $MgCl_2$	Expenditure (Current $)	$ 11,509,200	$ 4,474,650	$ 51,894,900	$ 55,887,700	$ 31,091,400	$ 48,860,050	$ 51,273,900	$ 3,483,350	$ 13,857,500	$ 23,156,400	$ 6,303,150	$ 13,706,850
	Present Worth	$ 11,509,200	$ 3,677,836	$ 35,058,335	$ 31,032,456	$ 14,189,709	$ 18,328,226	$ 15,808,701	$ 882,735	$ 2,886,365	$ 3,964,339	$ 886,933	$ 1,585,273

	Sum of Present Worths	Annuity
Option 1	$ 207,106,602	$ 9,154,494
Option 2	$ 139,810,107	$ 6,179,865
Difference	$ 67,296,495	$ 2,974,629

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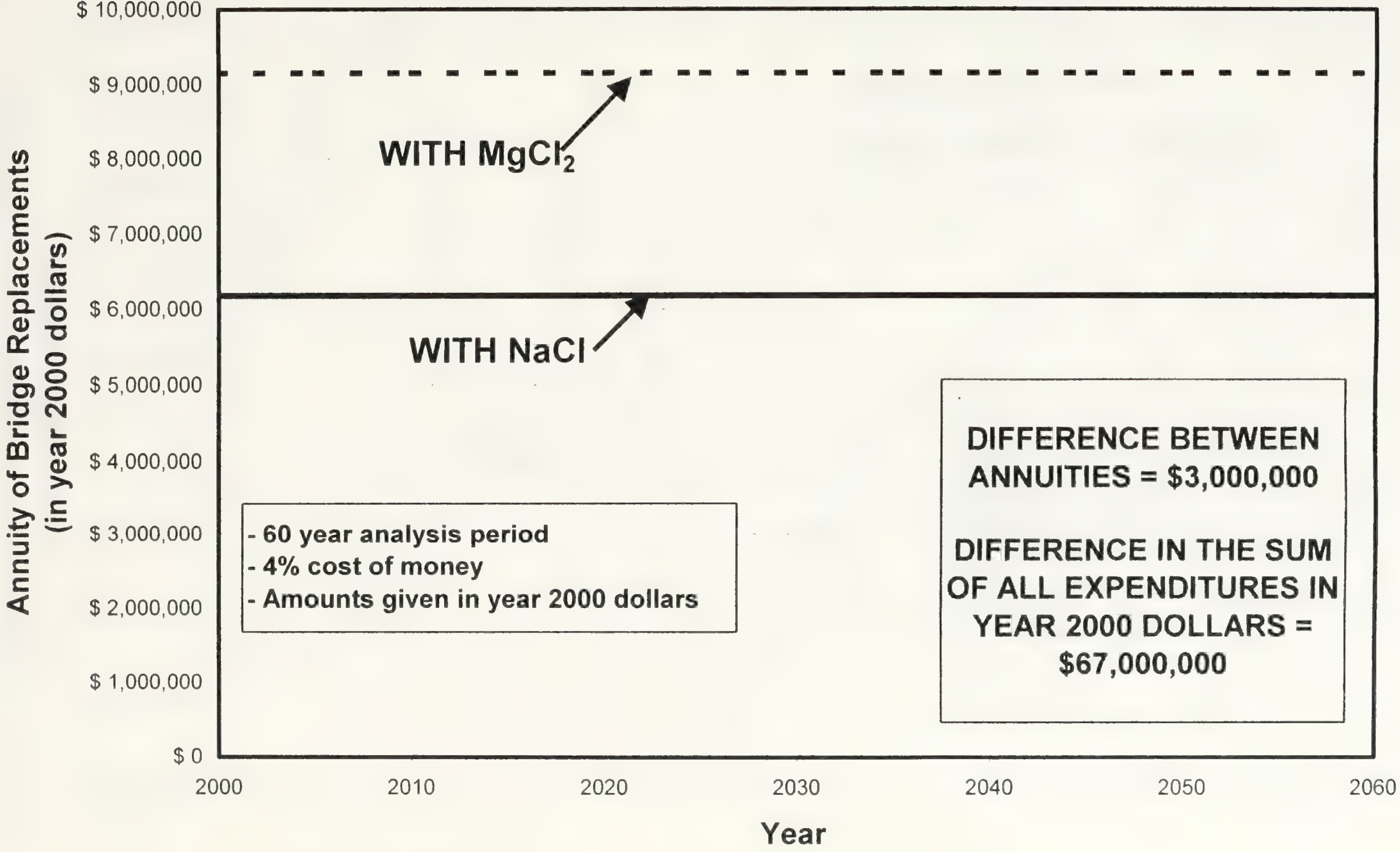
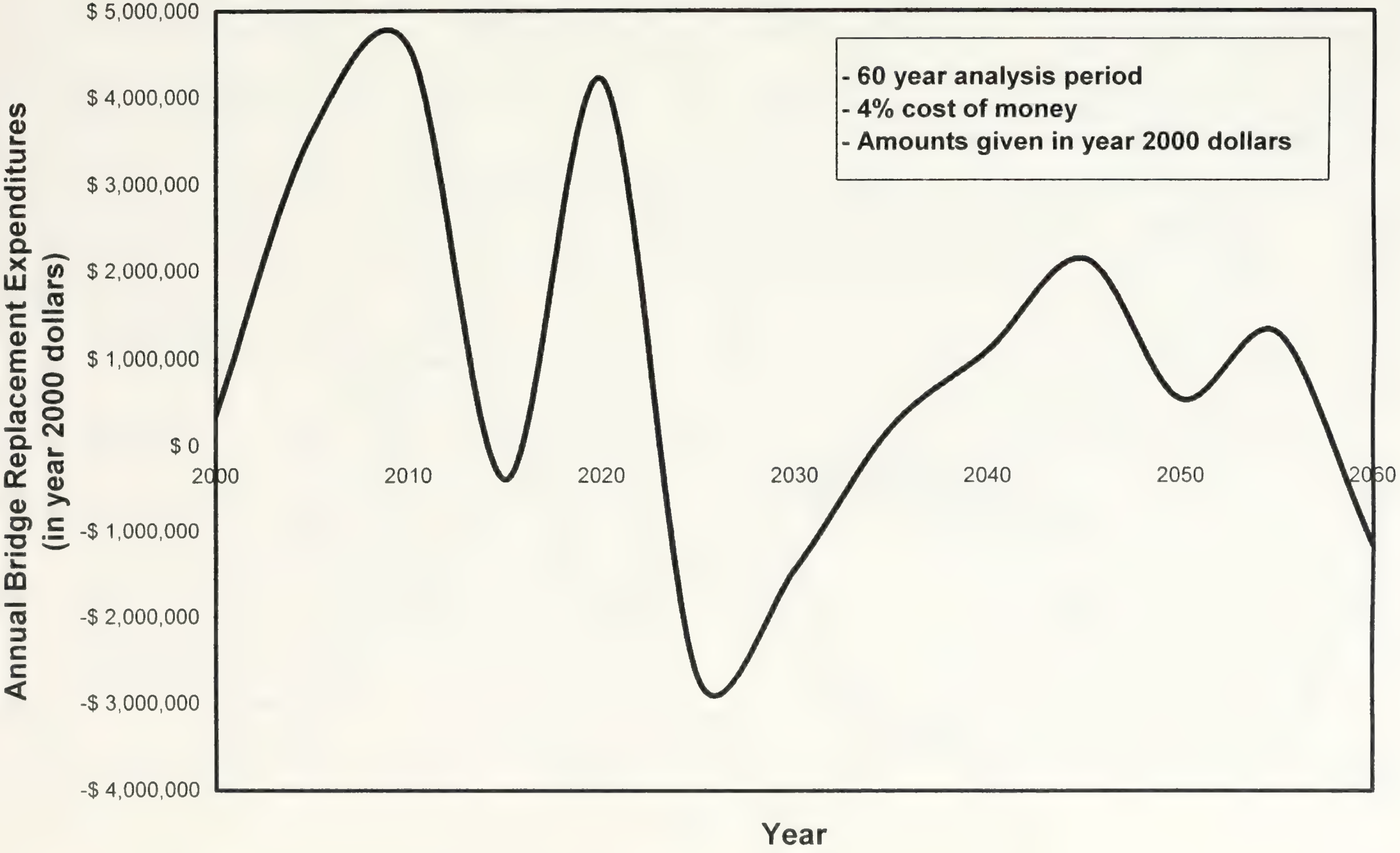
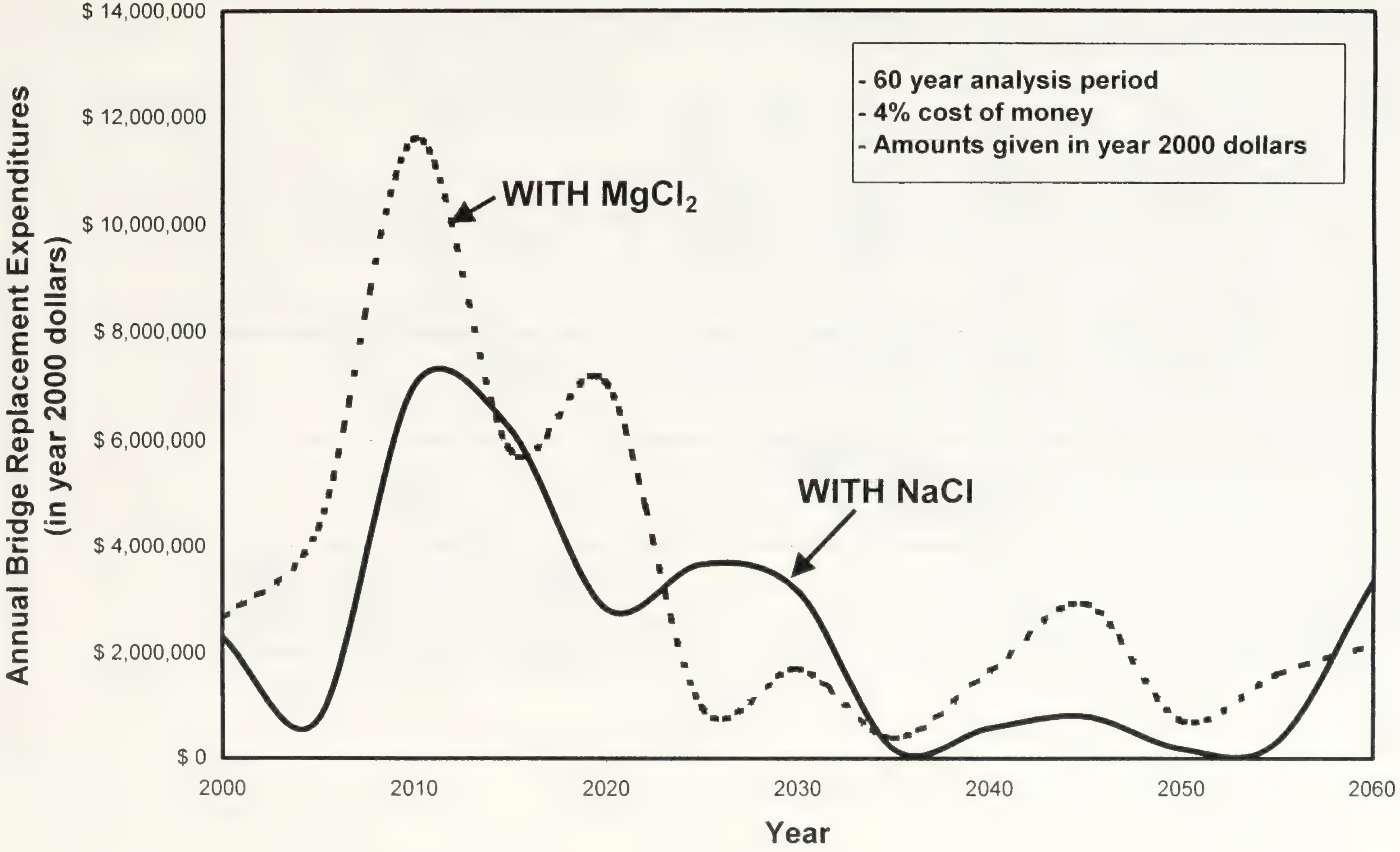
Future Average Bridge Replacement Needs for Current $MgCl_2$ Treated Bridges
Assuming $MgCl_2$ Reduces Service Life by 30%



Difference in Annual Bridge Replacement Needs If Partial System Treated with $MgCl_2$ vs NaCl Assuming $MgCl_2$ Reduces Service Life by 30%



Future Annual Bridge Replacement Needs If Partial System Treated Assuming $MgCl_2$ Reduces Service Life by 30%



Present Worth Analysis:
Future Replacement Needs of Currently $MgCl_2$ Treated Bridges
($MgCl_2$ decreases remaining life by 20%)
Future dollars with 6% increase for inflation & increased standards

Assumptions:

-2% = Value of Money; difference between bank interest rate and inflation rate
2000 = Current Year (for analysis purposes) (this is equal to 6% for inflation and increased standards)
20 = Analysis Period (years)

	Expenditure Year	2000	2005	2010	2015
Option 1	Expenditure Description	Bridge Replacements	Bridge Replacements	Bridge Replacements	Bridge Replacements
With $MgCl_2$	Expenditure (Current $)	$ 13,310,100	$ 18,388,500	$ 90,042,700	$ 33,116,550
	Present Worth	$ 13,310,100	$ 20,343,043	$ 110,201,563	$ 44,838,797
Option 2	Expenditure Description	Bridge Replacements	Bridge Replacements	Bridge Replacements	Bridge Replacements
Without $MgCl_2$	Expenditure (Current $)	$ 11,509,200	$ 4,474,650	$ 51,894,900	$ 55,887,700
	Present Worth	$ 11,509,200	$ 4,950,268	$ 63,513,189	$ 75,670,238

	Sum of Present Worths	**Annuity**
Option 1	**$ 188,693,503**	**$ 7,579,802**
Option 2	**$ 155,642,896**	**$ 6,252,162**

Difference	**$ 33,050,607**	**$ 1,327,640**

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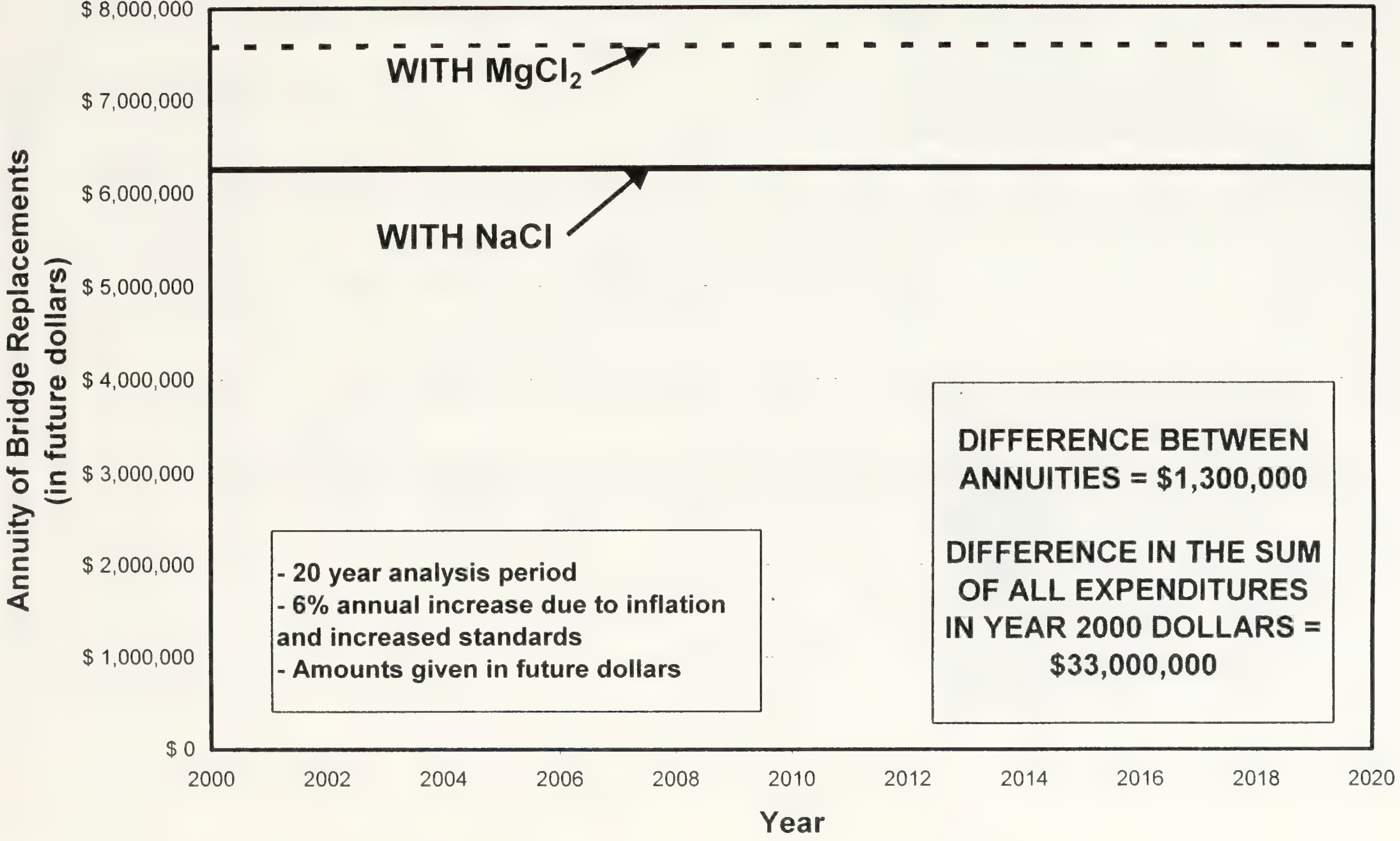


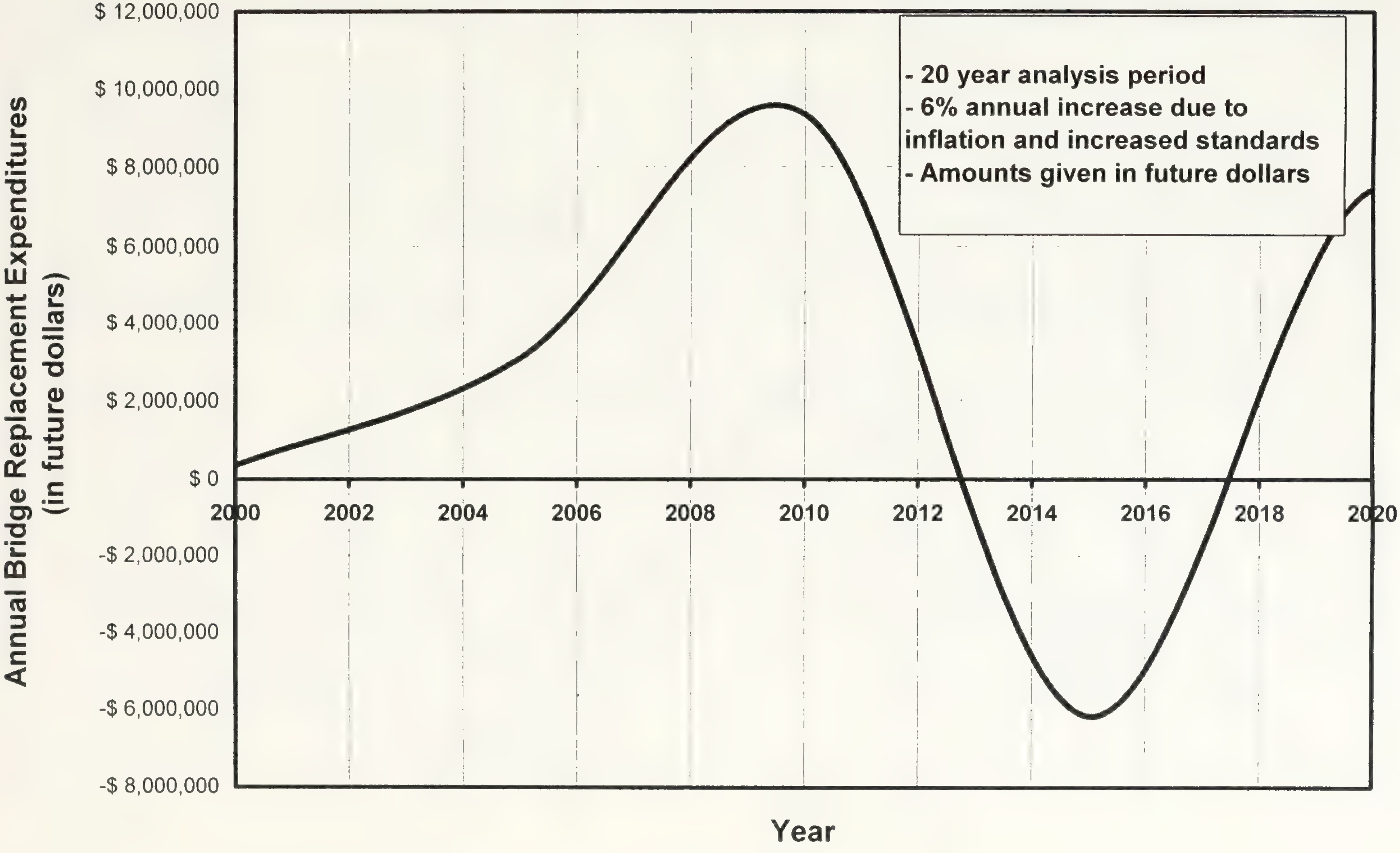
Future Average Bridge Replacement Needs for Current $MgCl_2$ Treated Bridges
Assuming $MgCl_2$ Reduces Service Life by 20%

- 20 year analysis period
- 6% annual increase due to inflation and increased standards
- Amounts given in future dollars

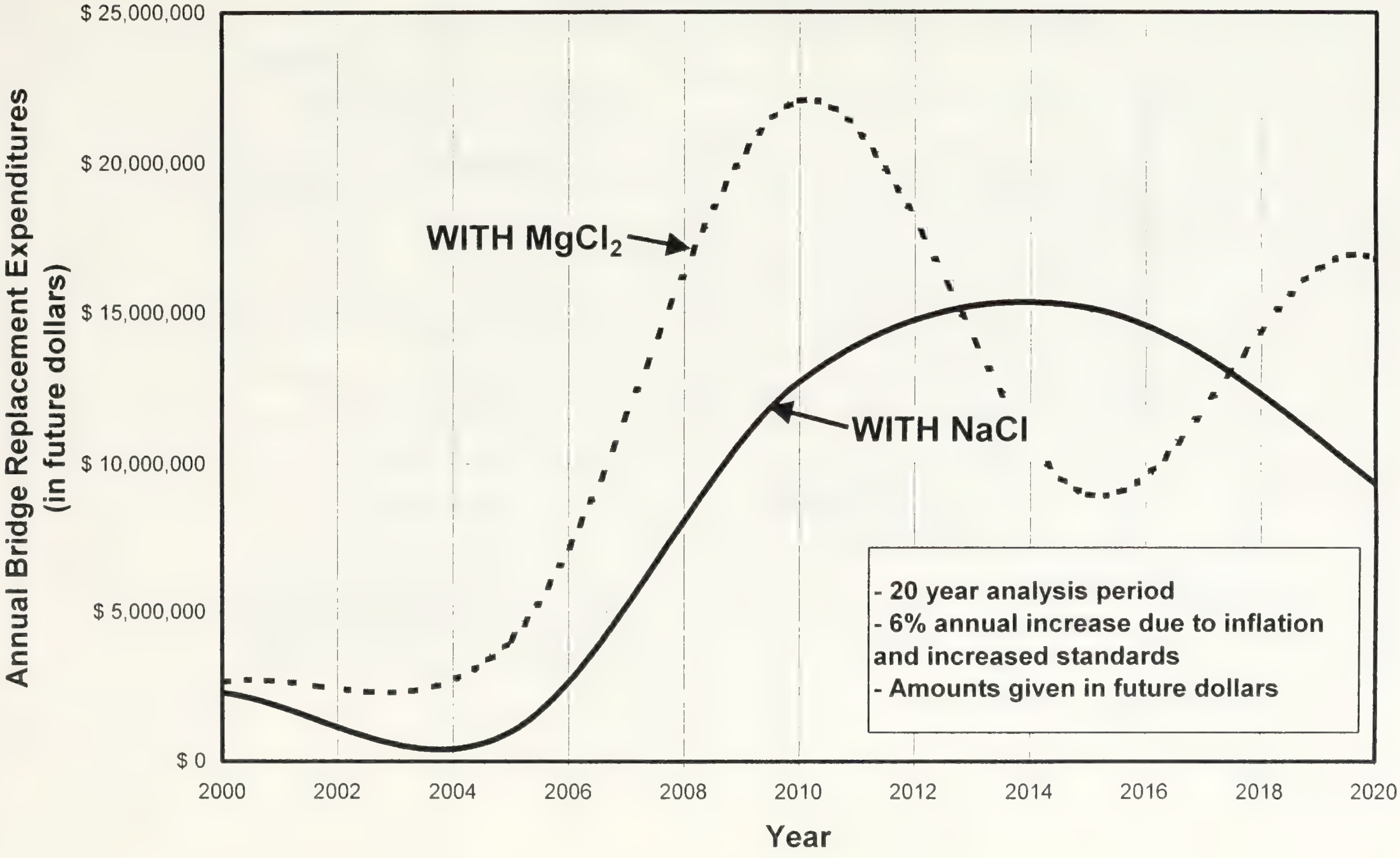
DIFFERENCE BETWEEN ANNUITIES = $1,300,000

DIFFERENCE IN THE SUM OF ALL EXPENDITURES IN YEAR 2000 DOLLARS = $33,000,000

Difference in Annual Bridge Replacement Needs If Partial System Treated with $MgCl_2$ vs NaCl Assuming $MgCl_2$ Reduces Service Life by 20%



Future Annual Bridge Replacement Needs If Partial System Treated Assuming $MgCl_2$ Reduces Service Life by 20%



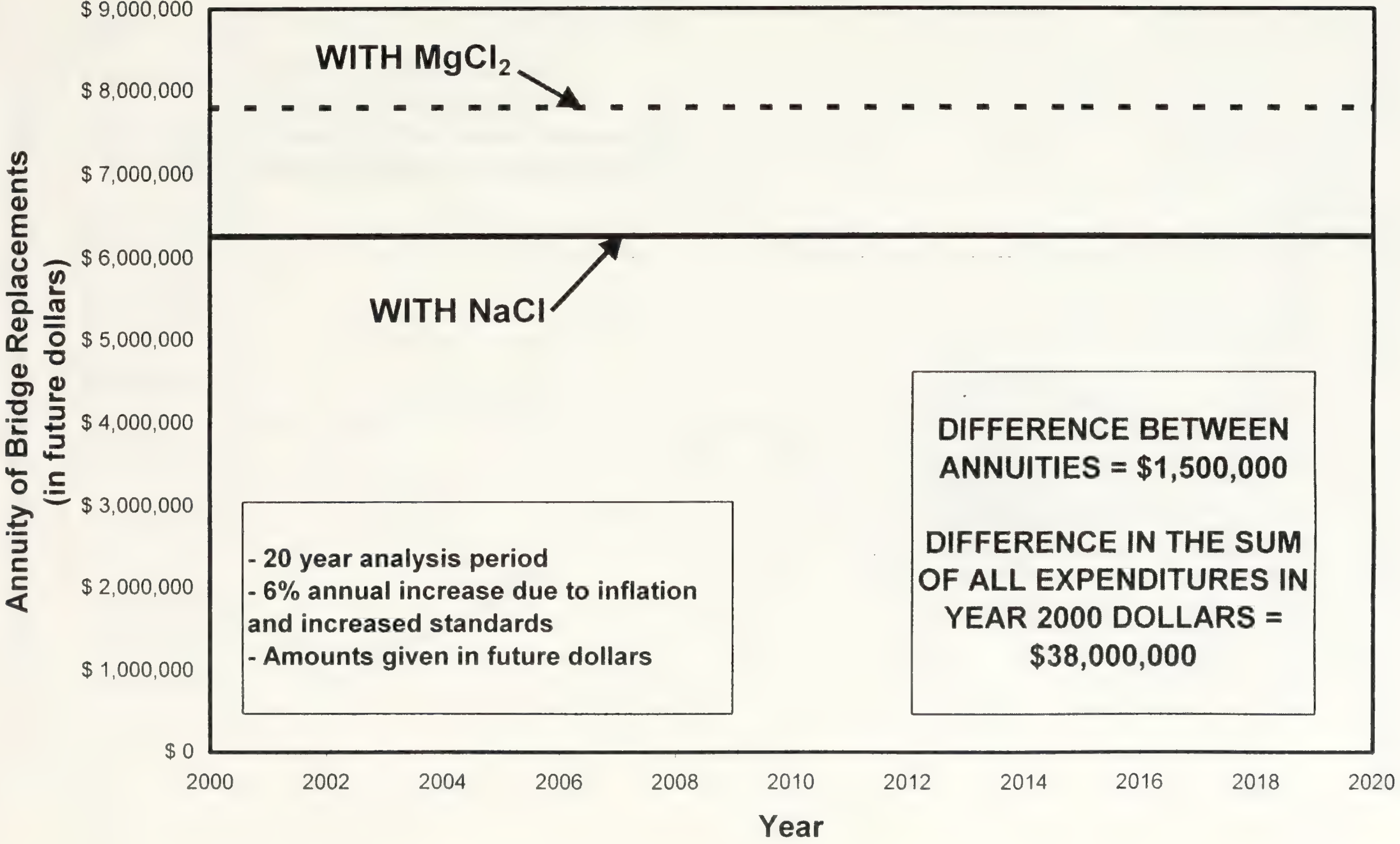
Present Worth Analysis:
Future Replacement Needs of Currently $MgCl_2$ Treated Bridges
($MgCl_2$ decreases remaining life by 25%)
Future dollars with 6% increase for inflation & increased standards

Assumptions:

-2% = Value of Money; difference between bank interest rate and inflation rate
2000 = Current Year (for analysis purposes) (this is equal to 6% inflation and increased standards)
20 = Analysis Period (years)

	Expenditure Year	2000	2005	2010	2015
Option 1	Expenditure Description	Bridge Replacements	Bridge Replacements	Bridge Replacements	Bridge Replacements
With $MgCl_2$	Expenditure (Current $)	$ 13,310,100	$ 24,173,000	$ 86,283,350	$ 35,682,200
	Present Worth	$ 13,310,100	$ 26,742,387	$ 105,600,565	$ 48,312,609
Option 2	Expenditure Description	Bridge Replacements	Bridge Replacements	Bridge Replacements	Bridge Replacements
Without $MgCl_2$	Expenditure (Current $)	$ 11,509,200	$ 4,474,650	$ 51,894,900	$ 55,887,700
	Present Worth	$ 11,509,200	$ 4,950,268	$ 63,513,189	$ 75,670,238

	Sum of Present Worths	**Annuity**
Option 1	**$ 193,965,661**	**$ 7,791,584**
Option 2	**$ 155,642,896**	**$ 6,252,162**
Difference	**$ 38,322,765**	**$ 1,539,422**



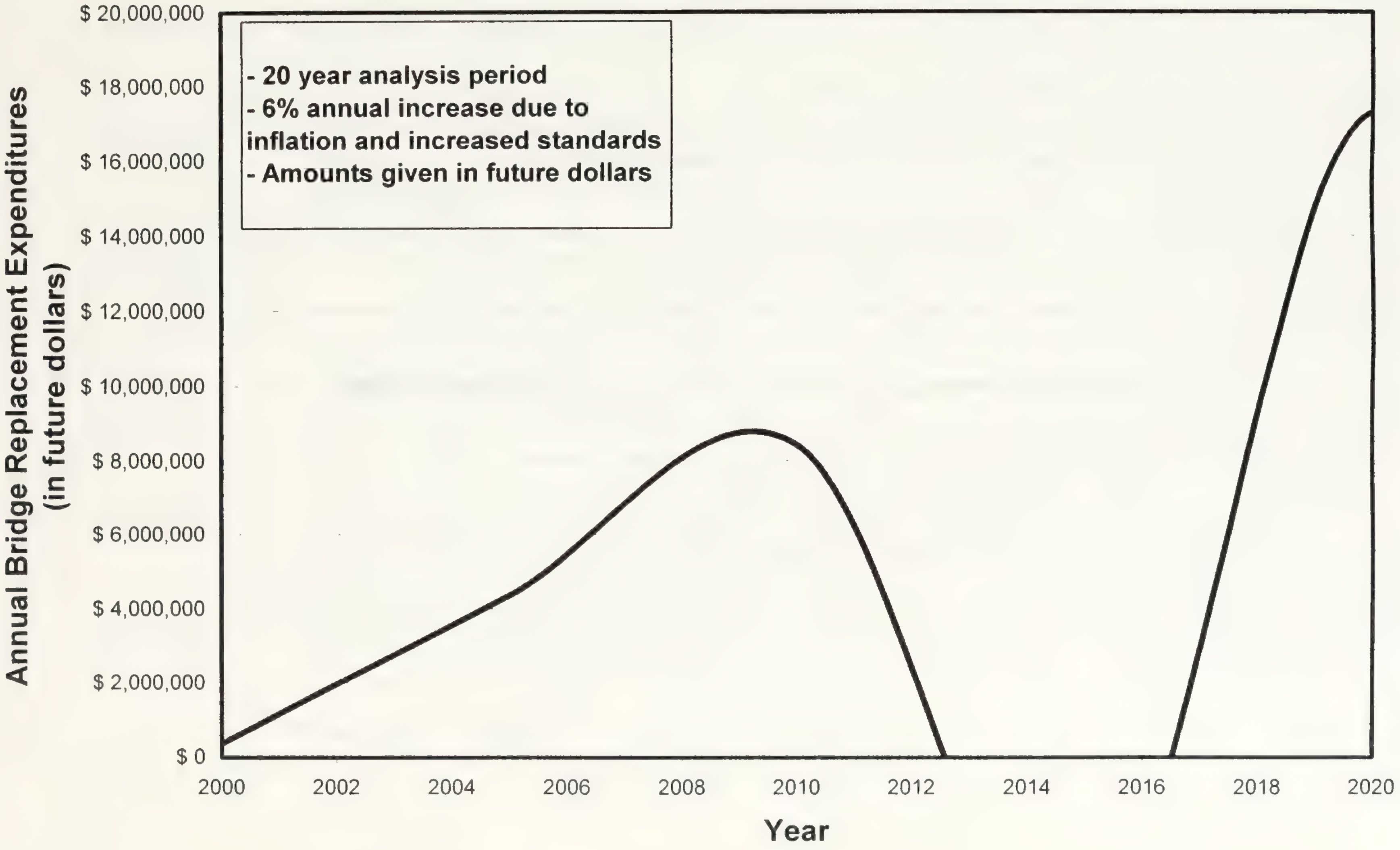
Future Average Bridge Replacement Needs for Current $MgCl_2$ Treated Bridges
Assuming $MgCl_2$ Reduces Service Life by 25%

- 20 year analysis period
- 6% annual increase due to inflation and increased standards
- Amounts given in future dollars

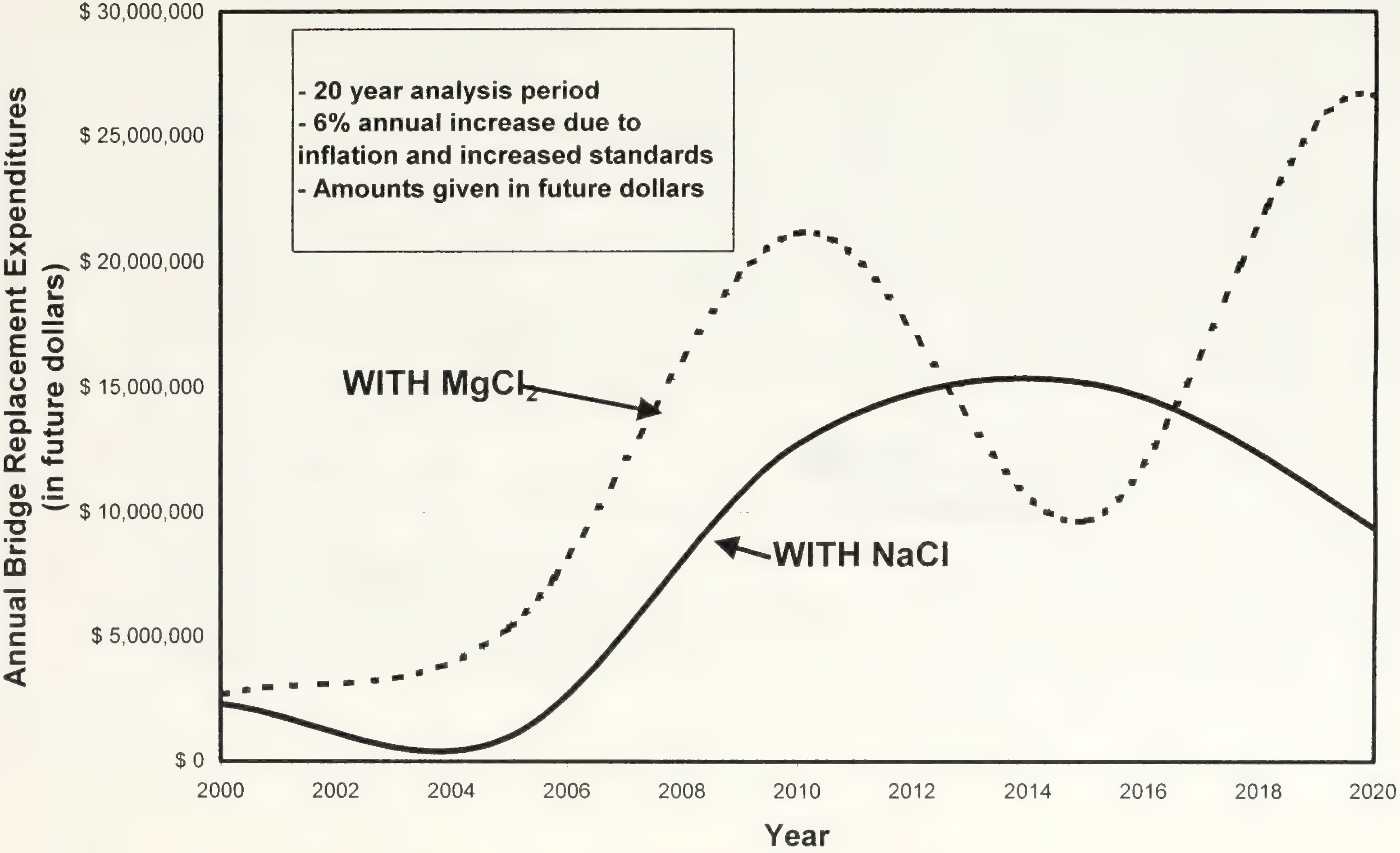
DIFFERENCE BETWEEN ANNUITIES = $1,500,000

DIFFERENCE IN THE SUM OF ALL EXPENDITURES IN YEAR 2000 DOLLARS = $38,000,000

Difference in Annual Bridge Replacement Needs If Partial System Treated with $MgCl_2$ vs NaCl Assuming $MgCl_2$ Reduces Service Life by 25%



Future Annual Bridge Replacement Needs If Partial System Treated Assuming $MgCl_2$ Reduces Service Life by 25%



- 20 year analysis period
- 6% annual increase due to inflation and increased standards
- Amounts given in future dollars

Future Replacement Needs of Currently $MgCl_2$ Treated Bridges
($MgCl_2$ decreases remaining life by 30%)
Future dollars with 6% increase for inflation & increased standards

Assumptions:

-2% = Value of Money; difference between bank interest rate and inflation rate
2000 = Current Year (for analysis purposes) (this is equal to 6% inflation and increased standards)
20 = Analysis Period (years)

	Expenditure Year	2000	2005	2010	2015
Option 1	Expenditure Description	Bridge Replacements	Bridge Replacements	Bridge Replacements	Bridge Replacements
With $MgCl_2$	Expenditure (Current $)	$ 13,310,100	$ 26,407,450	$ 85,808,400	$ 52,353,750
	Present Worth	$ 13,310,100	$ 29,214,341	$ 105,019,283	$ 70,885,378
Option 2	Expenditure Description	Bridge Replacements	Bridge Replacements	Bridge Replacements	Bridge Replacements
Without $MgCl_2$	Expenditure (Current $)	$ 11,509,200	$ 4,474,650	$ 51,894,900	$ 55,887,700
	Present Worth	$ 11,509,200	$ 4,950,268	$ 63,513,189	$ 75,670,238

	Sum of Present Worths	Annuity
Option 1	**$ 218,429,101**	**$ 8,774,278**
Option 2	**$ 155,642,896**	**$ 6,252,162**

Difference	**$ 62,786,206**	**$ 2,522,117**

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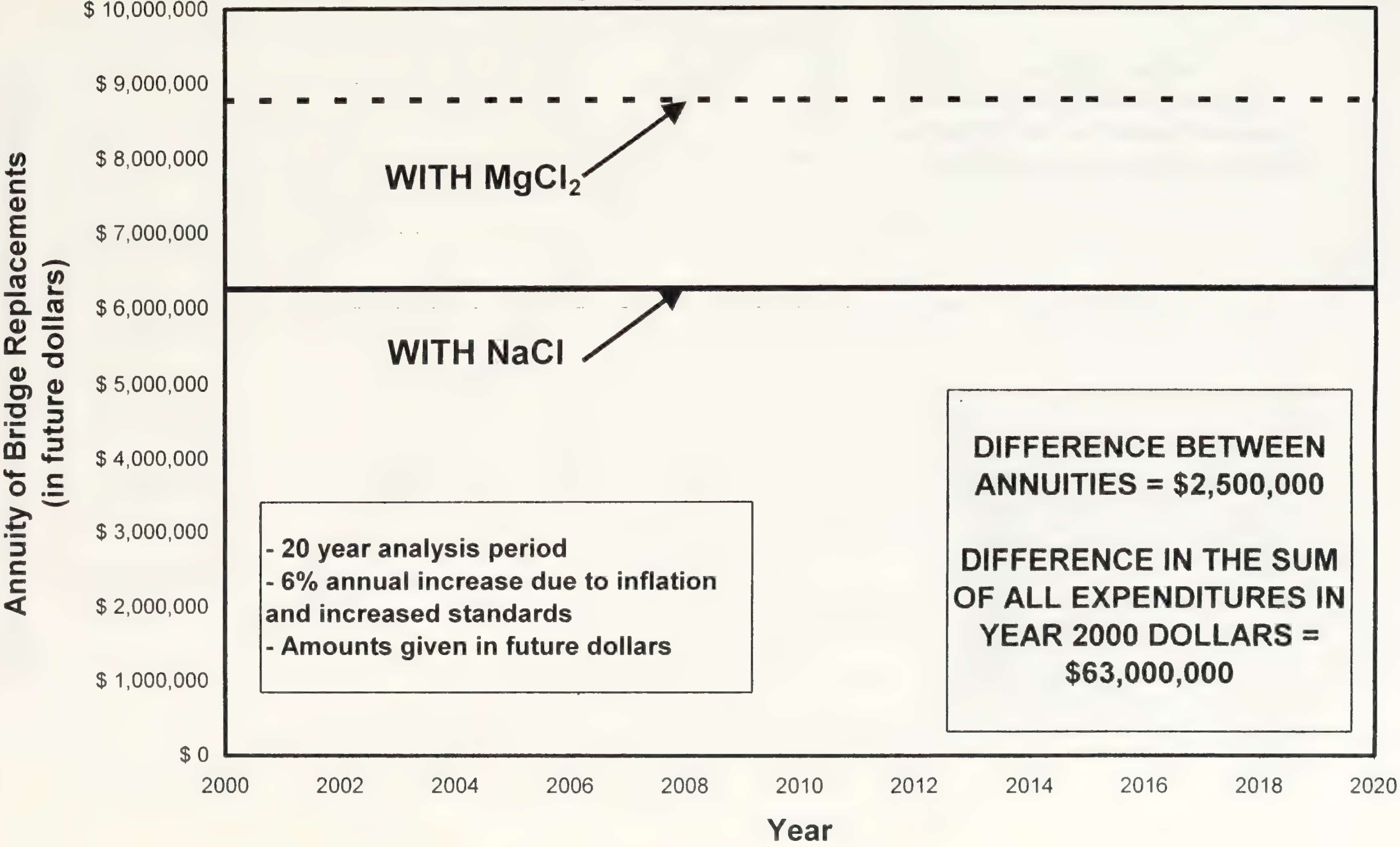


Future Average Bridge Replacement Needs for Current $MgCl_2$ Treated Bridges

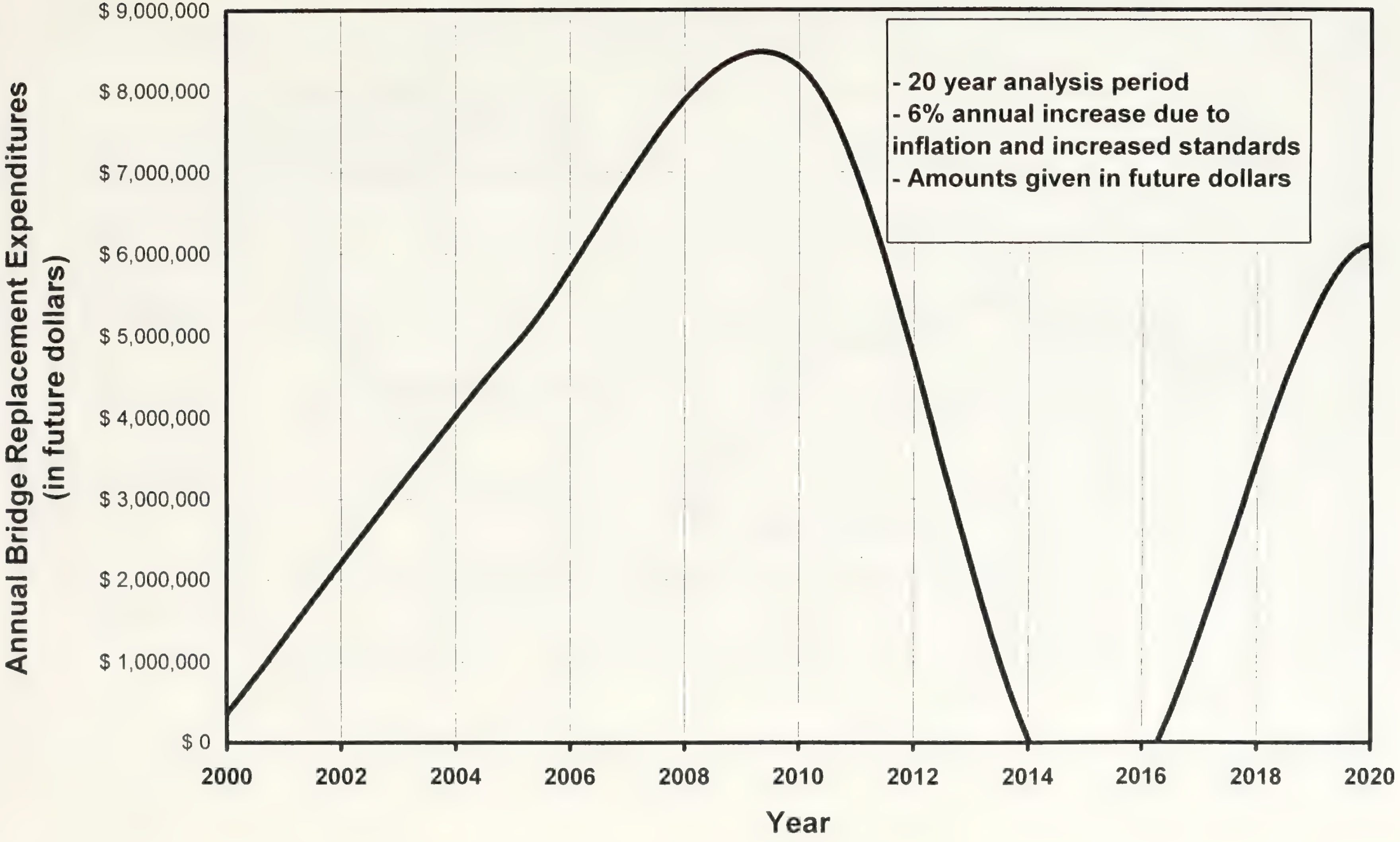
Assuming $MgCl_2$ Reduces Service Life by 30%

- 20 year analysis period
- 6% annual increase due to inflation and increased standards
- Amounts given in future dollars

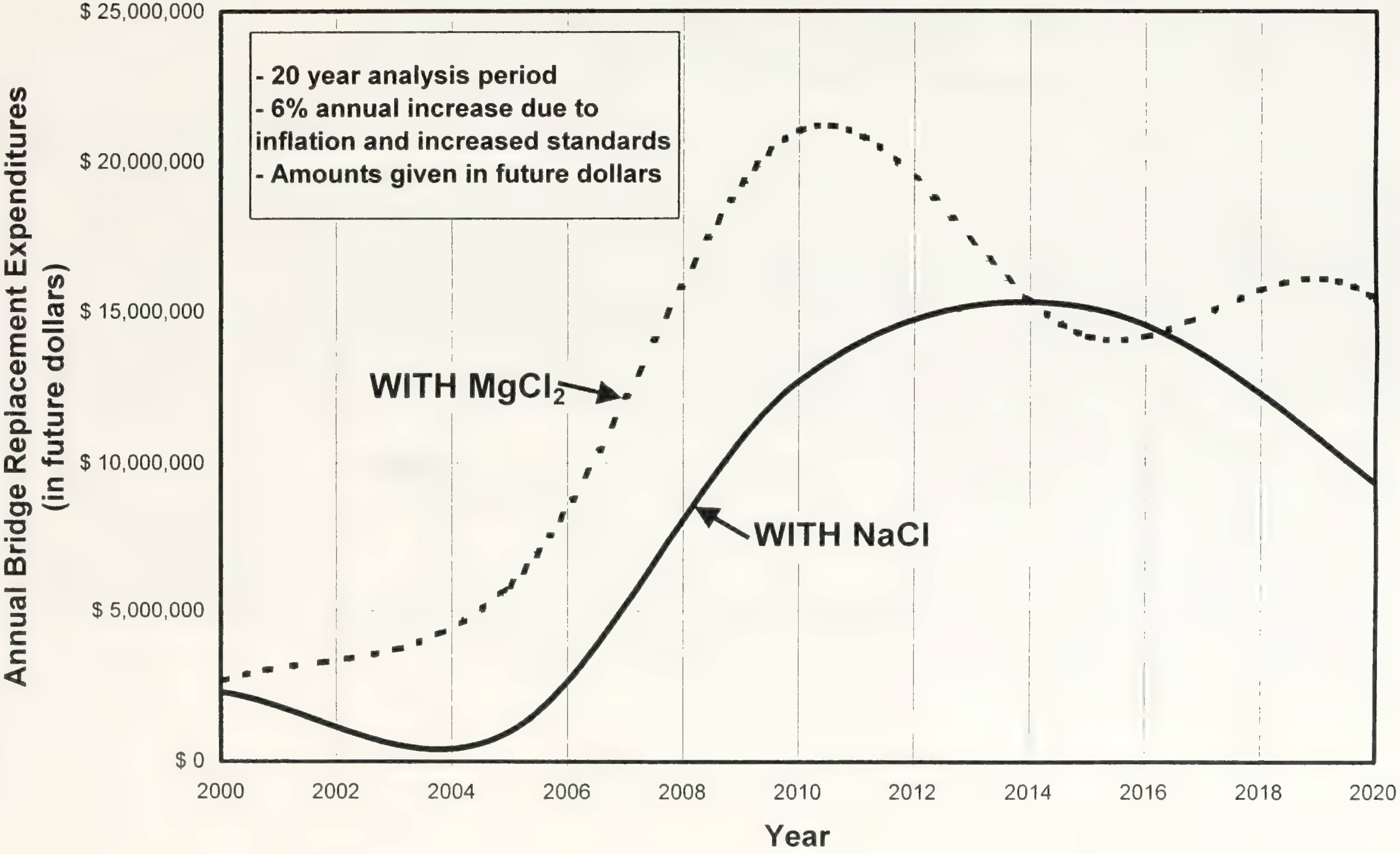
DIFFERENCE BETWEEN ANNUITIES = $2,500,000

DIFFERENCE IN THE SUM OF ALL EXPENDITURES IN YEAR 2000 DOLLARS = $63,000,000

Difference in Annual Bridge Replacement Needs If Partial System Treated with $MgCl_2$ vs NaCl Assuming $MgCl_2$ Reduces Service Life by 30%



Future Annual Bridge Replacement Needs If Partial System Treated Assuming $MgCl_2$ Reduces Service Life by 30%



Present Worth Analysis:
Future Replacement Needs of Currently $MgCl_2$ Treated Bridges
($MgCl_2$ decreases remaining life by 20%)
Future dollars with 6% increase for inflation & increased standards

Assumptions:

-2% = Value of Money, difference between bank interest rate and inflation rate (this is equal to 6% inflation and increased standards)
2000 = Current Year (for analysis purposes)
60 = Analysis Period (years)

	Expenditure Year	2000	2005	2010	2015	2020	2025	2030	2035	2040	2045	2050	2055
Option 1	Expenditure Description	Bridge Replacements	Bridge Replacements	Bridge Replacements	Bridge Replacements	Bridge Replacements	Bridge Replacements	Bridge Replacements	Bridge Replacements	Bridge Replacements	Bridge Replacements	Bridge Replacements	Bridge Replacements
With $MgCl_2$	Expenditure (Current $)	$ 13,310,100	$ 18,388,500	$ 90,042,700	$ 33,116,550	$ 55,918,750	$ 45,481,350	$ 14,933,900	$ 24,297,200	$ 7,669,350	$ 32,095,350	$ 93,484,650	$ 17,619,150
	Present Worth	$ 13,310,100	$ 20,343,043	$ 110,201,563	$ 44,838,797	$ 83,759,860	$ 75,367,039	$ 27,377,322	$ 49,276,923	$ 17,207,411	$ 79,665,211	$ 256,706,297	$ 53,524,275
Option 2	Expenditure Description	Bridge Replacements	Bridge Replacements	Bridge Replacements	Bridge Replacements	Bridge Replacements	Bridge Replacements	Bridge Replacements	Bridge Replacements	Bridge Replacements	Bridge Replacements	Bridge Replacements	Bridge Replacements
Without $MgCl_2$	Expenditure (Current $)	$ 11,509,200	$ 4,474,650	$ 51,894,900	$ 55,887,700	$ 31,091,400	$ 48,860,050	$ 51,273,900	$ 3,483,350	$ 13,857,500	$ 23,156,400	$ 6,303,150	$ 13,706,850
	Present Worth	$ 11,509,200	$ 4,950,268	$ 63,513,189	$ 75,670,238	$ 46,571,343	$ 80,965,875	$ 93,997,019	$ 7,064,549	$ 31,091,513	$ 57,477,469	$ 17,308,278	$ 41,639,307

	Sum of Present Worths	Annuity
Option 1	$ 831,577,840	$ 7,045,048
Option 2	$ 531,758,250	$ 4,505,005

Difference	$ 299,819,590	$ 2,540,043

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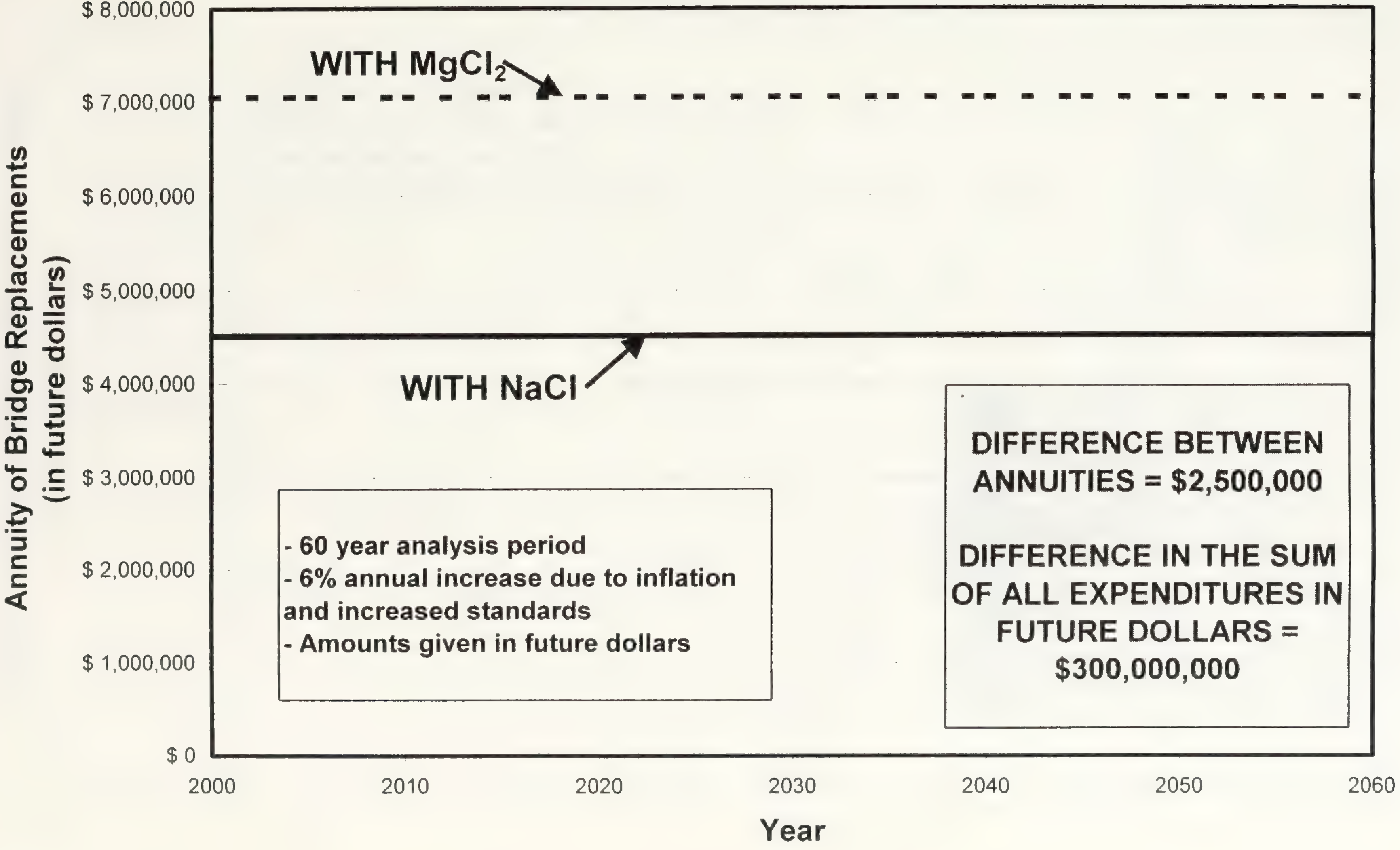
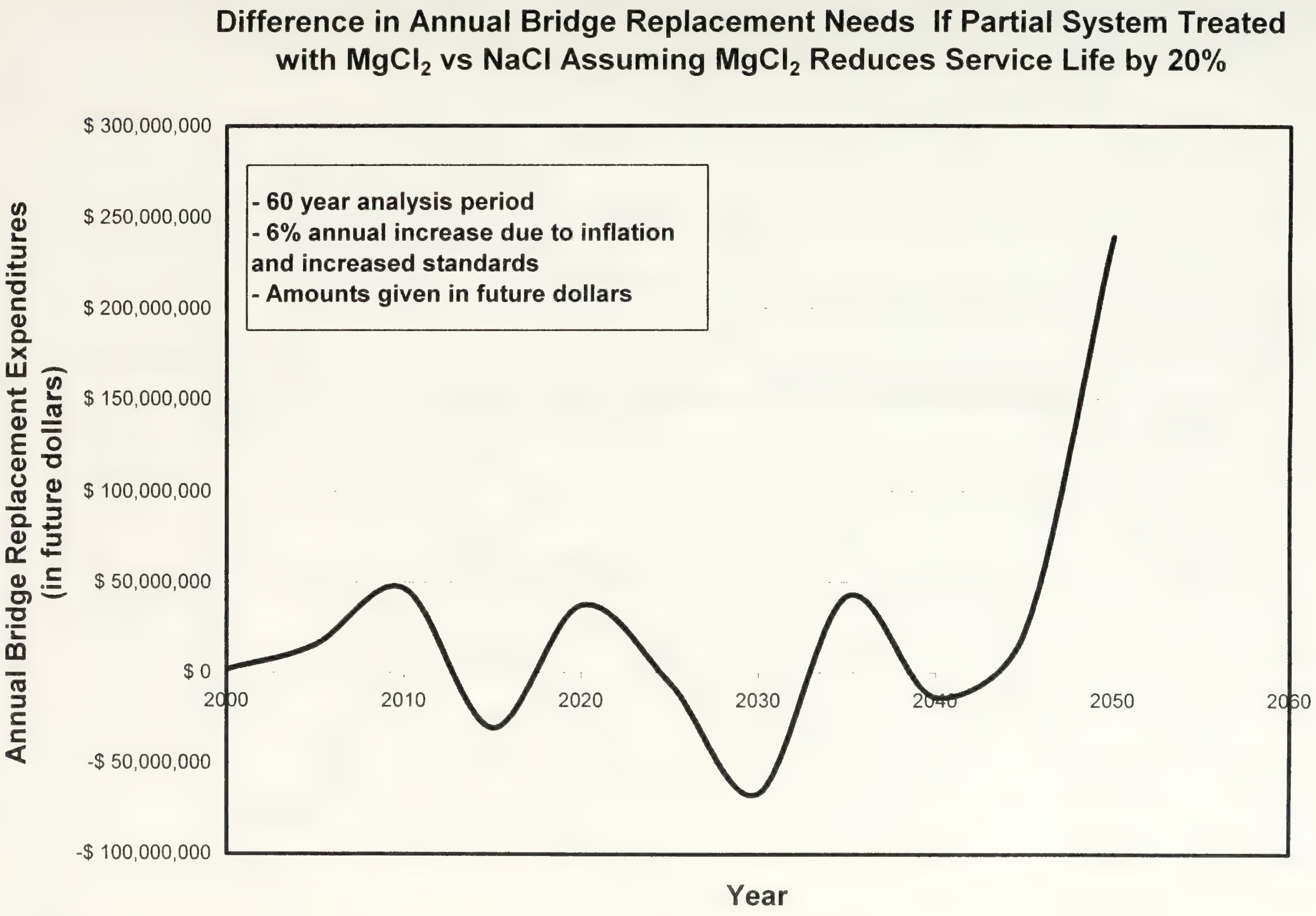
Future Average Bridge Replacement Needs for Current $MgCl_2$ Treated Bridges
Assuming $MgCl_2$ Reduces Service Life by 20%



- 60 year analysis period
- 6% annual increase due to inflation and increased standards
- Amounts given in future dollars

DIFFERENCE BETWEEN ANNUITIES = $2,500,000

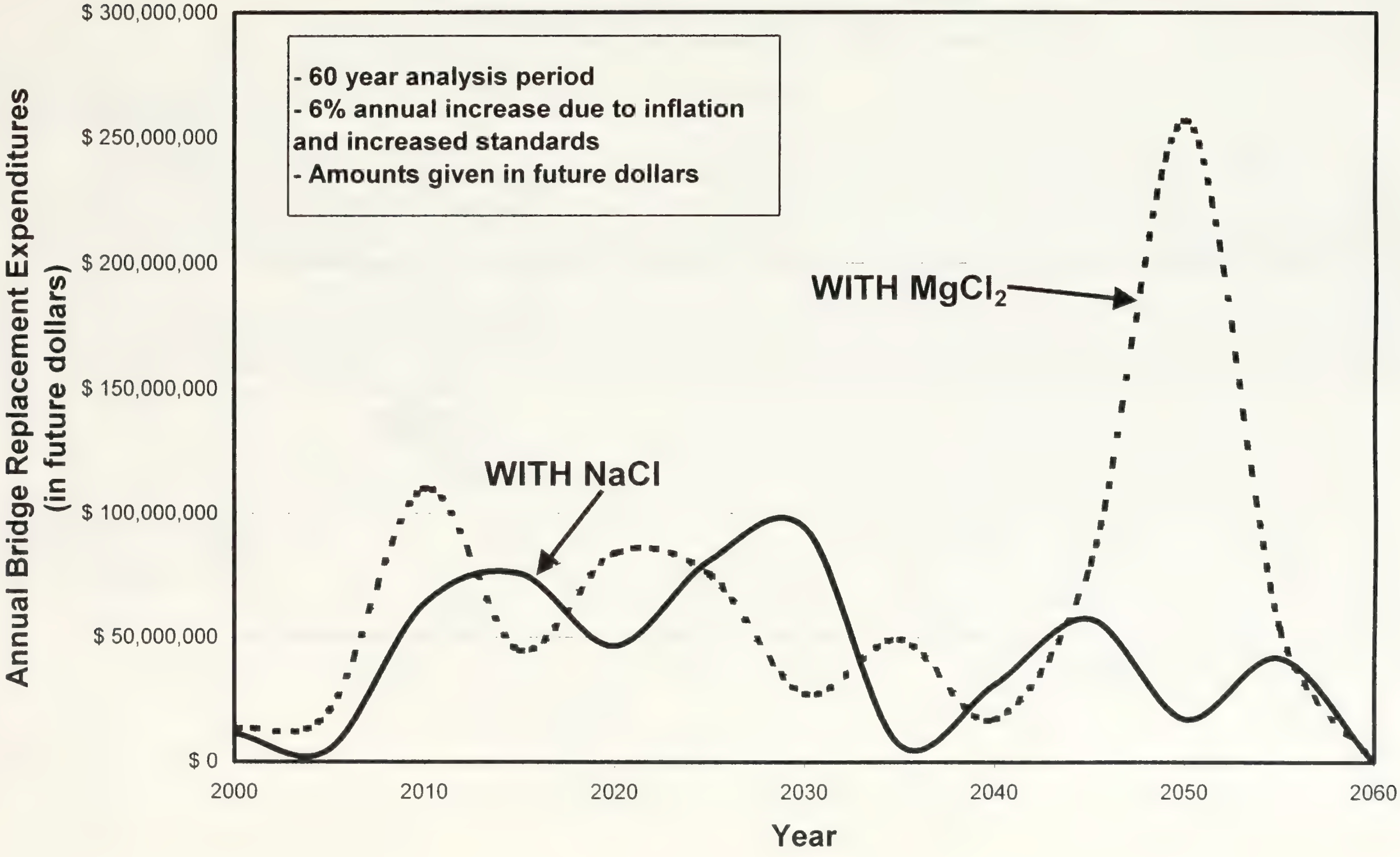
DIFFERENCE IN THE SUM OF ALL EXPENDITURES IN FUTURE DOLLARS = $300,000,000



Difference in Annual Bridge Replacement Needs If Partial System Treated with $MgCl_2$ vs NaCl Assuming $MgCl_2$ Reduces Service Life by 20%

- 60 year analysis period
- 6% annual increase due to inflation and increased standards
- Amounts given in future dollars

Future Annual Bridge Replacement Needs If Partial System Treated Assuming $MgCl_2$ Reduces Service Life by 20%



Present Worth Analysis:
Future Replacement Needs of Currently $MgCl_2$ Treated Bridges
($MgCl_2$ decreases remaining life by 25%, 6% inflation)

Assumptions:

-2% = Value of Money, difference between bank interest rate and inflation rate (this is equal to 6% inflation and increased standards)
2000 = Current Year (for analysis purposes)
60 = Analysis Period (years)

	Expenditure Year	2000	2005	2010	2015	2020	2025	2030	2035	2040	2045	2050	2055
Option 1	Expenditure Description	Bridge Replacements	Bridge Replacements	Bridge Replacements	Bridge Replacements	Bridge Replacements	Bridge Replacements	Bridge Replacements	Bridge Replacements	Bridge Replacements	Bridge Replacements	Bridge Replacements	Bridge Replacements
With $MgCl_2$	Expenditure (Current $)	$ 13,310,100	$ 24,173,000	$ 86,283,350	$ 35,682,200	$ 88,847,850	$ 10,178 650	$ 26,230,350	$ 16,560,000	$ 15,599,750	$ 67,482,000	$ 51,379,700	$ 21,829,300
	Present Worth	$ 13,310,100	$ 26,742,387	$ 105,600,565	$ 48,312,609	$ 133,083,866	$ 16,867 017	$ 48,086,350	$ 33,585,180	$ 35,000,529	$ 167,499,895	$ 141,087,254	$ 66,314,064
Option 2	Expenditure Description	Bridge Replacements	Bridge Replacements	Bridge Replacements	Bridge Replacements	Bridge Replacements	Bridge Replacements	Bridge Replacements	Bridge Replacements	Bridge Replacements	Bridge Replacements	Bridge Replacements	Bridge Replacements
Without $MgCl_2$	Expenditure (Current $)	$ 11,509,200	$ 4,474,650	$ 51,894,900	$ 55,887,700	$ 31,091,400	$ 48,860,050	$ 51,273,900	$ 3,483,350	$ 13,857,500	$ 23,156,400	$ 6,303,150	$ 13,706,850
	Present Worth	$ 11,509,200	$ 4,950,268	$ 63,513,189	$ 75,670,238	$ 46,571,343	$ 80,965,875	$ 93,997,019	$ 7,064,549	$ 31,091,513	$ 57,477,469	$ 17,308,278	$ 41,639,307

	Sum of Present Worths	Annuity
Option 1	$ 835,489,817	$ 7,078,190
Option 2	$ 531,758,250	$ 4,505,005

Difference	$ 303,731,567	$ 2,573,185

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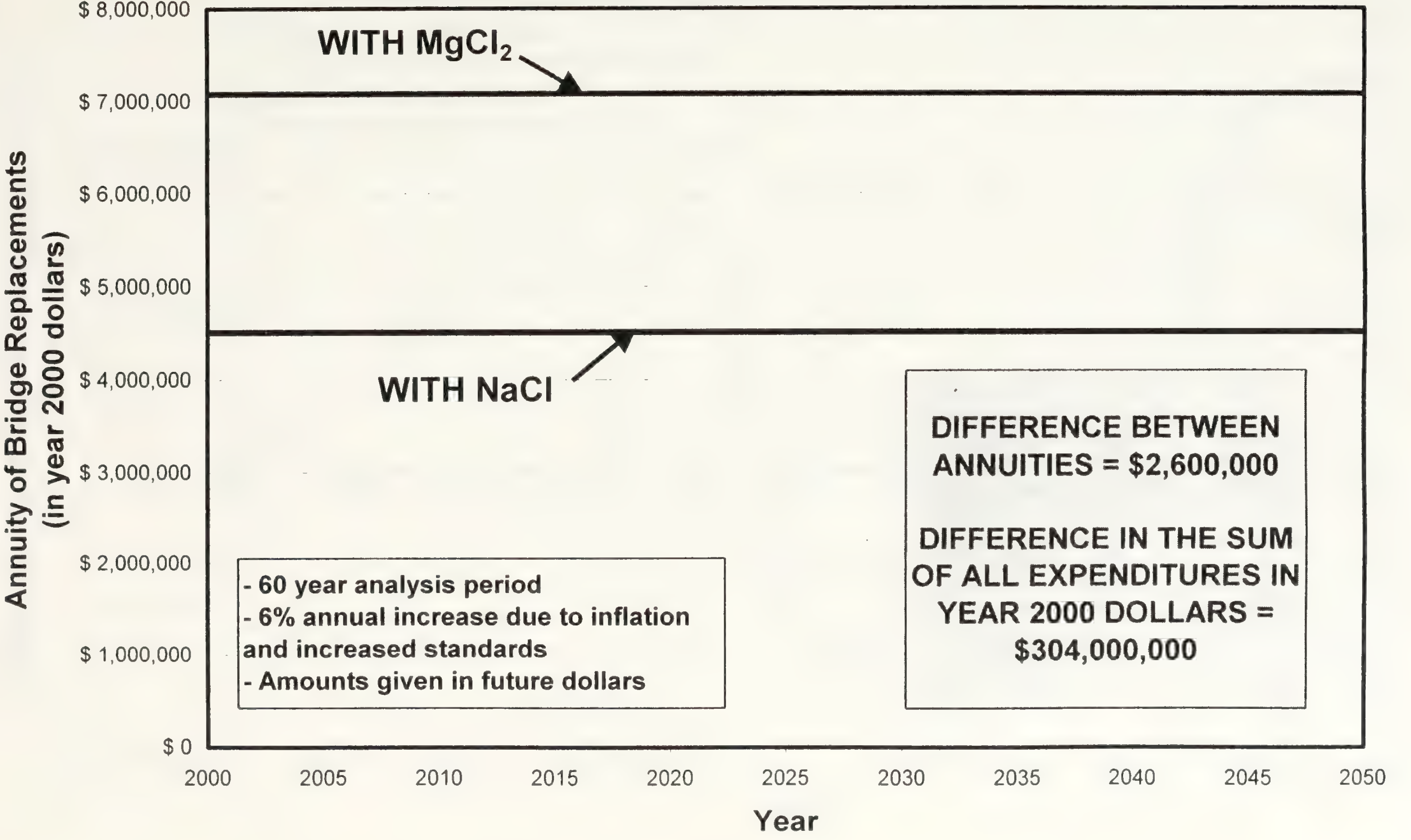
Future Average Bridge Replacement Needs for Current $MgCl_2$ Treated Bridges

Assuming $MgCl_2$ Reduces Service Life by 25%

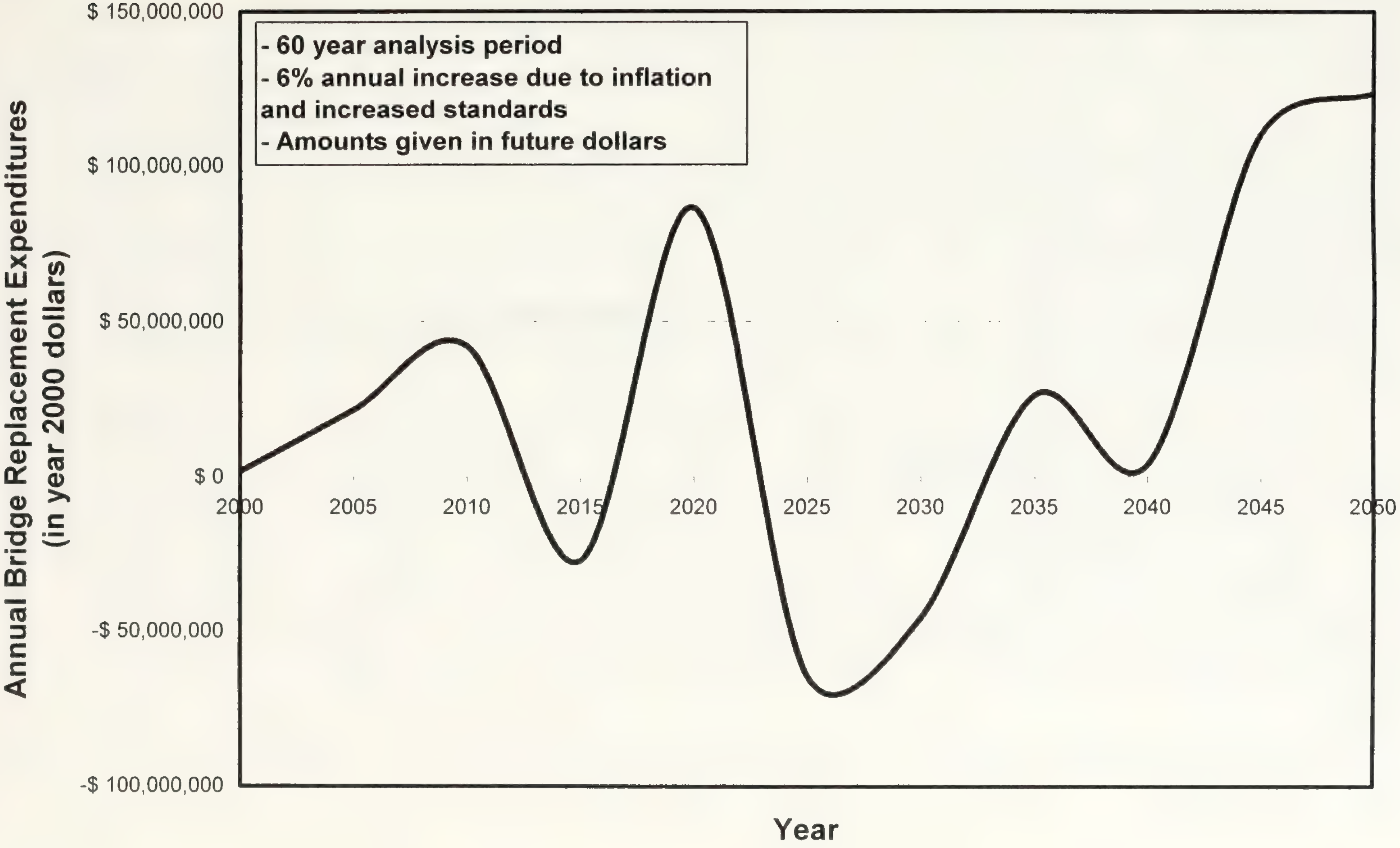


- 60 year analysis period
- 6% annual increase due to inflation and increased standards
- Amounts given in future dollars

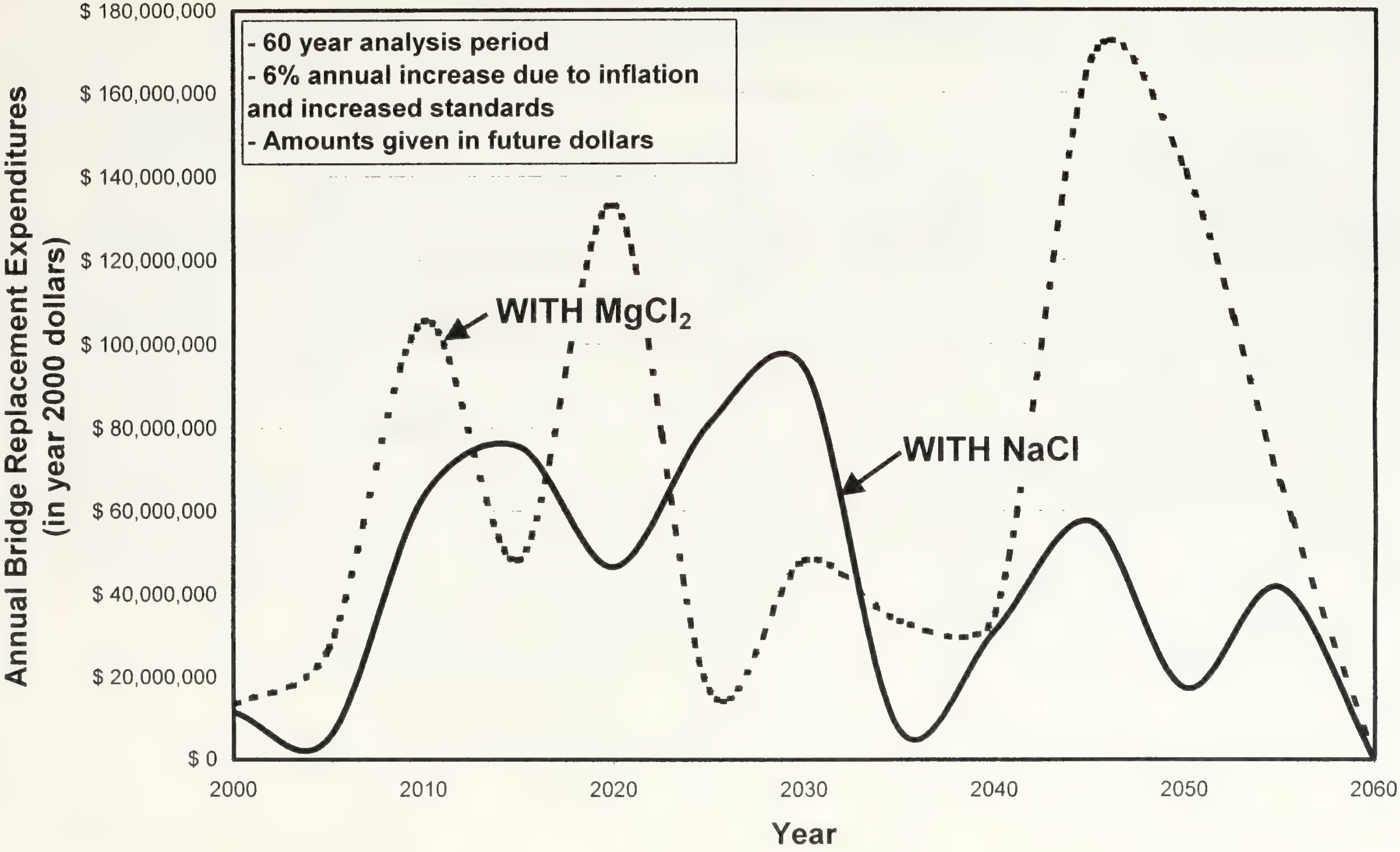
DIFFERENCE BETWEEN ANNUITIES = $2,600,000

DIFFERENCE IN THE SUM OF ALL EXPENDITURES IN YEAR 2000 DOLLARS = $304,000,000

Difference in Annual Bridge Replacement Needs If Partial System Treated with $MgCl_2$ vs NaCl Assuming $MgCl_2$ Reduces Service Life by 25%



Future Annual Bridge Replacement Needs If Partial System Treated Assuming $MgCl_2$ Reduces Service Life by 25%



Present Worth Analysis:
Future Replacement Needs of Currently $MgCl_2$ Treated Bridges
($MgCl_2$ decreases remaining life by 30%, 6% inflation)

Assumptions:

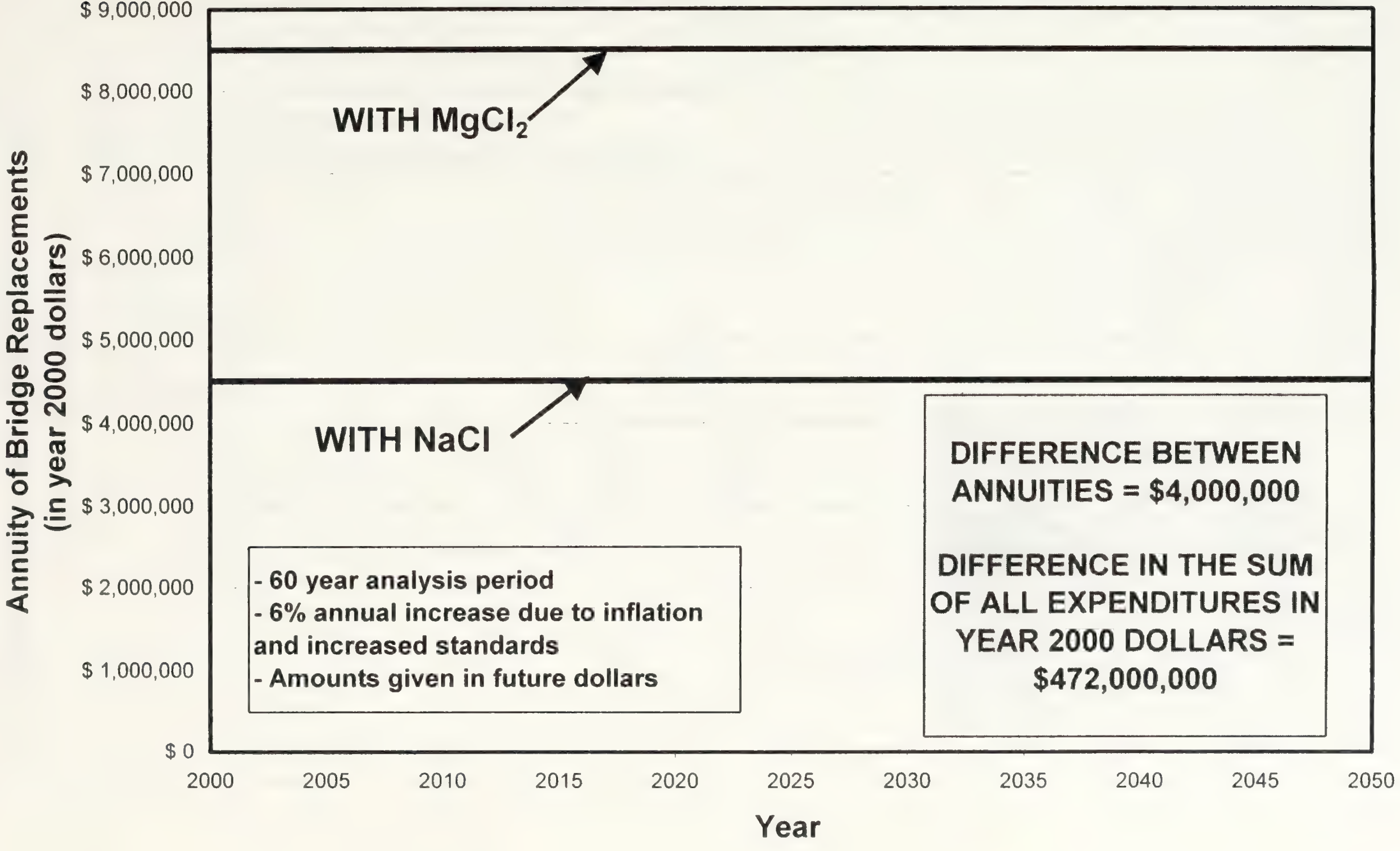
-2% = Value of Money, difference between bank interest rate and inflation rate (this is equal to 6% inflation and increased standards)
2000 = Current Year (for analysis purposes)
60 = Analysis Period (years)

	Expenditure Year	2000	2005	2010	2015	2020	2025	2030	2035	2040	2045	2050	2055
Option 1	Expenditure Description	Bridge Replacements	Bridge Replacements	Bridge Replacements	Bridge Replacements	Bridge Replacements	Bridge Replacements	Bridge Replacements	Bridge Replacements	Bridge Replacements	Bridge Replacements	Bridge Replacements	Bridge Replacements
With $MgCl_2$	Expenditure (Current $)	$ 13,310,100	$ 26,407,450	$ 85,808,400	$ 52,353,750	$ 77,112,100	$ 12,798,350	$ 27,698,900	$ 7,669,350	$ 40,114,300	$ 85,465,700	$ 25,346,000	$ 69,355,350
	Present Worth	$ 13,310,100	$ 29,214,341	$ 105,019,283	$ 70,885,378	$ 115,505,062	$ 21,208,116	$ 50,778,545	$ 15,554,137	$ 90,002,835	$ 212,137,989	$ 69,599,424	$ 210,690,913
Option 2	Expenditure Description	Bridge Replacements	Bridge Replacements	Bridge Replacements	Bridge Replacements	Bridge Replacements	Bridge Replacements	Bridge Replacements	Bridge Replacements	Bridge Replacements	Bridge Replacements	Bridge Replacements	Bridge Replacements
Without $MgCl_2$	Expenditure (Current $)	$ 11,509,200	$ 4,474,650	$ 51,894,900	$ 55,887,700	$ 31,091,400	$ 48,860,050	$ 51,273,900	$ 3,483,350	$ 13,857,500	$ 23,156,400	$ 6,303,150	$ 13,706,850
	Present Worth	$ 11,509,200	$ 4,950,268	$ 63,513,189	$ 75,670,238	$ 46,571,343	$ 80,965,875	$ 93,997,019	$ 7,064,549	$ 31,091,513	$ 57,477,469	$ 17,308,278	$ 41,639,307

	Sum of Present Worths	Annuity
Option 1	$ 1,003,906,122	$ 8,504,997
Option 2	$ 531,758,250	$ 4,505,005
Difference	$ 472,147,872	$ 3,999,992

Future Average Bridge Replacement Needs for Current $MgCl_2$ Treated Bridges

Assuming $MgCl_2$ Reduces Service Life by 30%

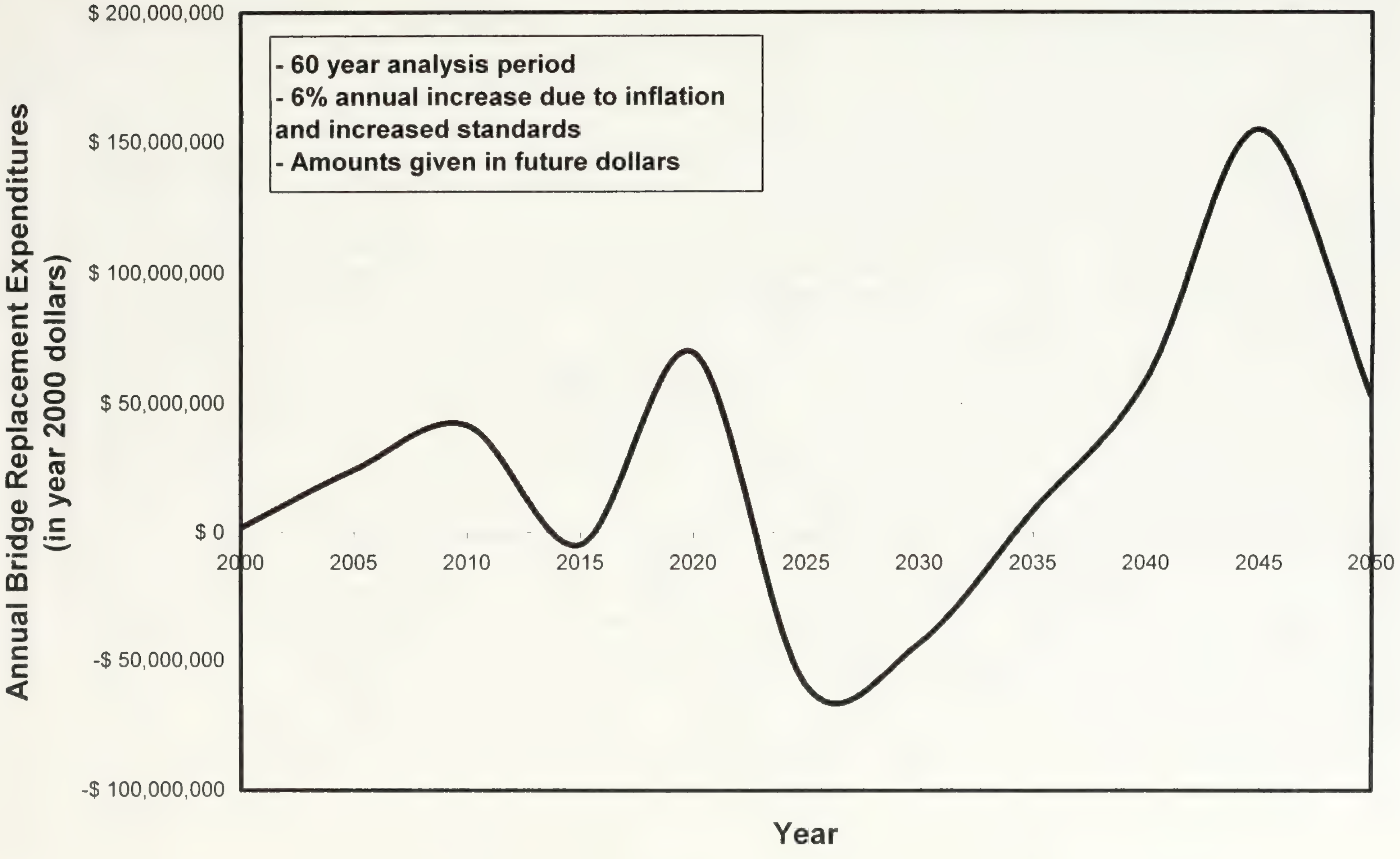


- 60 year analysis period
- 6% annual increase due to inflation and increased standards
- Amounts given in future dollars

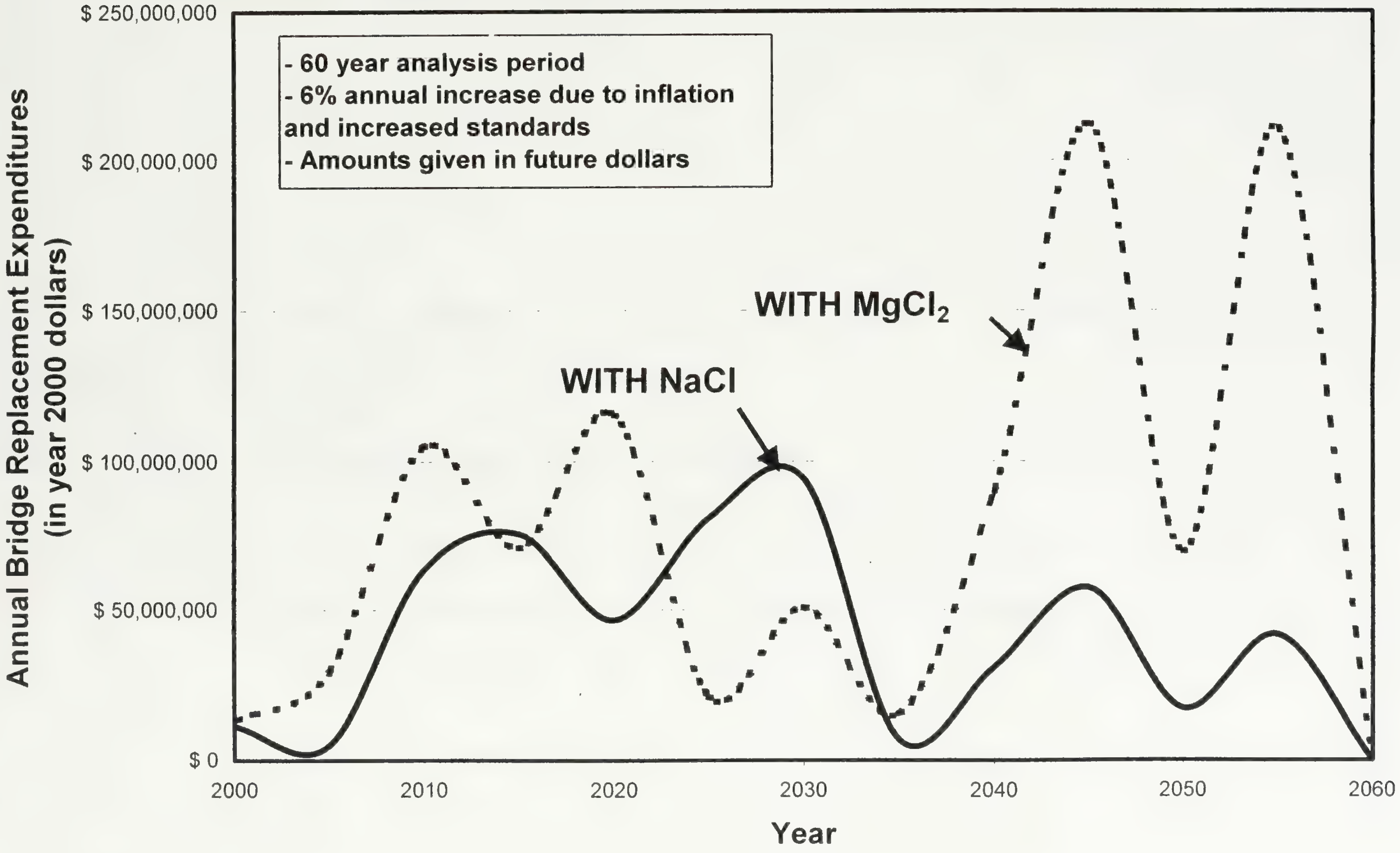
DIFFERENCE BETWEEN ANNUITIES = $4,000,000

DIFFERENCE IN THE SUM OF ALL EXPENDITURES IN YEAR 2000 DOLLARS = $472,000,000

Difference in Annual Bridge Replacement Needs If Partial System Treated with $MgCl_2$ vs NaCl Assuming $MgCl_2$ Reduces Service Life by 30%



Future Annual Bridge Replacement Needs If Partial System Treated Assuming $MgCl_2$ Reduces Service Life by 30%



APPENDIX D
BACKGROUND INFORMATION

Appendix D

Chloride Analysis Procedures

The Standard Potentiometric Titration, AASHTO T260-84

This method was used as the basis for comparison of the chloride content of the test samples. The following procedure was used. Three g of the powdered concrete sample are weighed to the nearest mg. Ten ml of 90 to 100°C distilled water are added and the sample is swirled. After the sample is in suspension, the slurry is ground to remove any lumps and then transferred into a beaker. Three ml of concentrated nitric acid are added to the remaining sample material, and this mixture is transferred quantitatively into the beaker while the slurry is stirred constantly. The solution is increased to approximately 50 ml by adding hot distilled water.

Five drops of methyl orange indicator are added to the slurry, and the pH of the sample is adjusted if needed. The solution is then covered with a watch glass and the stirring rod is left in the beaker. Next, the solution is heated, allowed to boil for 1 minute, and then removed from the heat. The sample is filtered into another beaker and the beaker, filter paper, funnel, and stirring rod are rinsed thoroughly to ensure complete transfer of the chloride. Finally, the sample is allowed to cool to room temperature.

Four ml of 0.01N NaCl solution are added to the sample prior to titration with 0.01N $AgNO_3$ solution. A chloride specific electrode, Orion Model 94-17B, its reference electrode, and a millivoltmeter are used in the determination of the titration end-point.

Analytical Services

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LEVELTON
Engineering Solutions

CHEMICAL ANALYSIS REPORT

Report:	**Analysis of Concrete Samples**	**Report Date:**	May 19, 1999
Client:	**Reid Crowther** 300 - 12420 - 104 Avenue Edmonton, Alberta T5N 3Z9	**Date Received:**	May 4, 1999
		File:	499-0376
Attention:	**Paul Carter**	**WO#:**	90509
Re:	**Montana DOT Study, File # 77054-00**		

Method of Testing

All tests were conducted according to AASHTO Method T-260 (Acid Soluble Test Method), involving extraction with hot nitric acid, filtration, and potentiometric titration. Duplicates were performed on every tenth sample, and a reference standard was run after every set of twenty samples.

Results of Testing

All duplicates were within acceptance criteria of ± 10% of sample test result. Reference samples also consistently agreed within ± 10%. Please refer to attached spreadsheet for all sample data.

Levelton Engineering Ltd.

Stephen Varisco, B.Sc.
Project Chemist

Final Review: Dr. T. F. (Tom) Guthrie, P.Ag.
Manager, Analytical Services

TFG:cc
90509.rpt

Certified by the Canadian Association for Environmental Analytical Laboratories (CAEAL) for specific environmental tests listed in the Registration Status Report.

LAB CHLORIDE RESULTS (% of Dry Weight)

	File No.	Sample	Test 1	Test 2	Difference	Average
1	01+ 9821	1A	0.029			
	01+ 9821	2A	0.130			
	01+ 9821	2B	0.046			
	01+ 9821	2C	0.015	0.017	0.002	0.016
	01+ 9821	3A	0.140			
	01+ 9821	3B	0.044			
	01+ 9821	3C	0.010			
	01+ 9821	4A	0.039			
	01+ 9821	4B	0.010			
	01+ 9821	5A	0.230			
	01+ 9821	5B	0.120			
	01+ 9821	5C	0.052			
	01+ 9821	6A	0.220			
	01+ 9821	6B	0.140			
	01+ 9821	6C	0.048			
	01+ 9821	6D	0.015			
	01+ 9821	7A	0.270	0.280	0.010	0.275
	01+ 9821	7B	0.130			
	01+ 9821	7C	0.029			
	01+ 9821	8A	0.210			
	Reference Std. #3		0.046			
2	05 + 1481	1A	0.170	0.170		0.170
	05 + 1481	2A	0.150			
	05 + 1481	2B	0.027			
	05 + 1481	2C	0.012			
	05 + 1481	3A	0.130			
	05 + 1481	3B	0.033			
	05 + 1481	3C	0.011			
	05 + 1481	4A	0.120			
	05 + 1481	4B	0.049			
	05 + 1481	5A	0.220			
	05 + 1481	5B	0.061	0.056	0.005	0.059
	05 + 1481	5C	0.008			
	05 + 1481	6A	0.230			
	05 + 1481	6B	0.100			
	05 + 1481	6C	0.010			
	05 + 1481	6D	0.011			
	05 + 1481	7A	0.180			
	05 + 1481	7B	0.110			
	05 + 1481	7C	0.020			
	05 + 1481	8A	0.310			
	Reference Std. #3		0.048			

3	06 + 5481	1A	0.065	0.067	0.002	0.066
	06 + 5481	2A	0.047			
	06 + 5481	2B	0.012			
	06 + 5481	2C	0.016			
	06 + 5481	3A	0.027			
	06 + 5481	3B	0.008			
	06 + 5481	3C	0.008			
	06 + 5481	4A	0.075			
	06 + 5481	4B	0.028			
	06 + 5481	5A	0.130			
	06 + 5481	5B	0.060	0.059	0.001	0.060
	06 + 5481	5C	0.034			
	06 + 5481	6A	0.100			
	06 + 5481	6B	0.033			
	06 + 5481	6C	0.013			
	06 + 5481	6D	0.009			
	06 + 5481	7A	0.099			
	06 + 5481	7B	0.041			
	06 + 5481	7C	0.009			
	06 + 5481	8A	0.090			
	Reference Std. #3		0.046			
4	10 + 1221	1A	0.014	0.015	0.001	0.015
	10 + 1221	2A	0.016			
	10 + 1221	2B	0.009			
	10 + 1221	2C	0.006			
	10 + 1221	3A	0.022			
	10 + 1221	3B	0.010			
	10 + 1221	3C	0.007			
	10 + 1221	4A	0.035			
	10 + 1221	4B	0.017			
	10 + 1221	5A	0.150			
	10 + 1221	5B	0.061	0.062	0.001	0.061
	10 + 1221	5C	0.009			
	10 + 1221	6A	0.150			
	10 + 1221	6B	***0.055***		revised	
	10 + 1221	6C	***0.008***		revised	
	10 + 1221	6D	0.009			
	10 + 1221	7A	0.130			
	10 + 1221	7B	0.044			
	10 + 1221	7C	0.009			
	10 + 1221	8A	0.059			
	Reference Std. #3		0.046			

5	10 + 7441	1A	0.059	0.057	0.002	0.058
	10 + 7441	2A	0.070			
	10 + 7441	2B	0.027			
	10 + 7441	2C	0.009			
	10 + 7441	3A	0.076			
	10 + 7441	3B	0.031			
	10 + 7441	3C	0.011			
	10 + 7441	4A	0.062			
	10 + 7441	4B	0.011			
	10 + 7441	5A	0.120			
	10 + 7441	5B	0.027	0.029	0.002	0.028
	10 + 7441	5C	0.008			
	10 + 7441	6A	0.230			
	10 + 7441	6B	0.028			
	10 + 7441	6C	0.012			
	10 + 7441	6D	0.008			
	10 + 7441	7A	0.095			
	10 + 7441	7B	0.013			
	10 + 7441	7C	0.014			
	10 + 7441	8A	0.170			
	Reference Std. #3		0.045			
6	23 + 631	1A	0.052	0.052		0.052
	23 + 631	2A	0.026			
	23 + 631	2B	0.008			
	23 + 631	2C	0.007			
	23 + 631	3A	0.028			
	23 + 631	3B	0.007			
	23 + 631	3C	0.006			
	23 + 631	4A	0.033			
	23 + 631	4B	0.008			
	23 + 631	5A	0.250			
	23 + 631	5B	0.100	0.100		0.100
	23 + 631	5C	0.035			
	23 + 631	6A	0.190			
	23 + 631	6B	0.078			
	23 + 631	6C	0.010			
	23 + 631	6D	0.015			
	23 + 631	7A	0.270			
	23 + 631	7B	0.078			
	23 + 631	7C	0.020			
	23 + 631	8A	0.230			
	Reference Std. #3		0.047			

7	29 + 2051	1A	0.076	0.083	0.007	0.080
	29 + 2051	2A	0.074			
	29 + 2051	2B	0.034			
	29 + 2051	2C	0.015			
	29 + 2051	3A	0.073			
	29 + 2051	3B	0.049			
	29 + 2051	3C	0.048			
	29 + 2051	4A	0.059			
	29 + 2051	4B	0.049			
	29 + 2051	5A	0.230			
	29 + 2051	5B	0.120	0.120		0.120
	29 + 2051	5C	0.060			
	29 + 2051	6A	0.280			
	29 + 2051	6B	0.190			
	29 + 2051	6C	0.100			
	29 + 2051	6D	0.018			
	29 + 2051	7A	0.300			
	29 + 2051	7B	0.180			
	29 + 2051	7C	0.080			
	29 + 2051	8A	0.270			
	Reference Std. #3		0.047			
8	29 + 2052	1A	0.035	0.035		0.035
	29 + 2052	2A	0.033			
	29 + 2052	2B	0.023			
	29 + 2052	2C	0.014			
	29 + 2052	3A	0.034			
	29 + 2052	3B	0.021			
	29 + 2052	3C	0.015			
	29 + 2052	4A	0.044			
	29 + 2052	4B	0.031			
	29 + 2052	5A	0.170			
	29 + 2052	5B	0.130	0.120	0.010	0.130
	29 + 2052	5C	0.063			
	29 + 2052	6A	0.190			
	29 + 2052	6B	0.078			
	29 + 2052	6C	0.023			
	29 + 2052	6D	0.014			
	29 + 2052	7A	0.170			
	29 + 2052	7B	0.096			
	29 + 2052	7C	0.025			
	29 + 2052	8A	0.200			
	Reference Std. #3		0.046			

9	29 + 3682	1A	0.083	0.080	0.003	0.082
	29 + 3682	2A	0.074			
	29 + 3682	2B	0.012			
	29 + 3682	2C	0.011			
	29 + 3682	3A	0.056			
	29 + 3682	3B	0.017			
	29 + 3682	3C	0.010			
	29 + 3682	4A	0.067			
	29 + 3682	4B	0.013			
	29 + 3682	5A	0.240			
	29 + 3682	5B	0.120	0.110	0.010	0.120
	29 + 3682	5C	0.039			
	29 + 3682	6A	0.220			
	29 + 3682	6B	0.110			
	29 + 3682	6C	0.035			
	29 + 3682	6D	0.009			
	29 + 3682	7A	0.250			
	29 + 3682	7B	0.160			
	29 + 3682	7C	0.075			
	29 + 3682	8A	0.230			
	Reference Std. #3		0.045			
10	34 + 2081	1A	0.051	0.051		0.051
	34 + 2081	2A	0.039			
	34 + 2081	2B	0.031			
	34 + 2081	2C	0.025			
	34 + 2081	3A	0.020			
	34 + 2081	3B	0.007			
	34 + 2081	3C	0.007			
	34 + 2081	4A	0.043			
	34 + 2081	4B	0.018			
	34 + 2081	5A	0.170			
	34 + 2081	5B	0.062	0.061	0.001	0.062
	34 + 2081	5C	0.021			
	34 + 2081	6A	0.180			
	34 + 2081	6B	0.035			
	34 + 2081	6C	0.009			
	34 + 2081	6D	0.009			
	34 + 2081	7A	0.140			
	34 + 2081	7B	0.031			
	34 + 2081	7C	0.008			
	34 + 2081	8A	0.130			
	Reference Std. #3		0.047			

11	34 + 2082	1A	0.021	0.022	0.001	0.022
	34 + 2082	2A	0.054			
	34 + 2082	2B	0.009			
	34 + 2082	2C	0.007			
	34 + 2082	3A	0.036			
	34 + 2082	3B	0.021			
	34 + 2082	3C	0.008			
	34 + 2082	4A	0.036			
	34 + 2082	4B	0.024			
	34 + 2082	5A	0.160			
	34 + 2082	5B	0.048	0.047	0.001	0.048
	34 + 2082	5C	0.013			
	34 + 2082	6A	0.240			
	34 + 2082	6B	0.083			
	34 + 2082	6C	0.009			
	34 + 2082	6D	0.007			
	34 + 2082	7A	0.200			
	34 + 2082	7B	0.059			
	34 + 2082	7C	0.009			
	34 + 2082	8A	0.160			
	Reference Std. #3		0.044			
12	39 + 8052	1A	0.100	0.110	0.010	0.110
	39 + 8052	2A	0.067			
	39 + 8052	2B	0.025			
	39 + 8052	2C	0.009			
	39 + 8052	3A	0.093			
	39 + 8052	3B	0.024			
	39 + 8052	3C	0.007			
	39 + 8052	4A	0.080			
	39 + 8052	4B	0.022			
	39 + 8052	5A	0.190			
	39 + 8052	5B	0.080	0.083	0.003	0.082
	39 + 8052	5C	0.009			
	39 + 8052	6A	0.100			
	39 + 8052	6B	0.015			
	39 + 8052	6C	0.009			
	39 + 8052	6D	0.008			
	39 + 8052	7A	0.180			
	39 + 8052	7B	0.100			
	39 + 8052	7C	0.021			
	39 + 8052	8A	0.120			
	Reference Std. #3		0.045			

13	39 + 9911	1A	0.056	0.055	0.001	0.056
	39 + 9911	2A	0.074			
	39 + 9911	2B	0.056			
	39 + 9911	2C	0.052			
	39 + 9911	3A	0.055			
	39 + 9911	3B	0.040			
	39 + 9911	3C	0.017			
	39 + 9911	4A	0.050			
	39 + 9911	4B	0.027			
	39 + 9911	5A	0.200			
	39 + 9911	5B	0.100	0.097	0.003	0.099
	39 + 9911	5C	0.046			
	39 + 9911	6A	0.260			
	39 + 9911	6B	0.087			
	39 + 9911	6C	0.056			
	39 + 9911	6D	0.015			
	39 + 9911	7A	0.290			
	39 + 9911	7B	0.100			
	39 + 9911	7C	0.053			
	39 + 9911	8A	0.190			
	Reference Std. #3		0.046			
14	39 + 9912	1A	0.078	0.077	0.001	0.078
	39 + 9912	2A	0.079			
	39 + 9912	2B	0.012			
	39 + 9912	2C	0.007			
	39 + 9912	3A	0.071			
	39 + 9912	3B	0.017			
	39 + 9912	3C	0.009			
	39 + 9912	4A	0.042			
	39 + 9912	4B	0.009			
	39 + 9912	5A	0.180			
	39 + 9912	5B	0.020	0.019	0.001	0.020
	39 + 9912	5C	0.083	0.087	0.004	0.085
	39 + 9912	6A	0.150			
	39 + 9912	6B	0.042			
	39 + 9912	6C	0.007			
	39 + 9912	6D	0.007			
	39 + 9912	7A	0.094			
	39 + 9912	7B	0.029			
	39 + 9912	7C	0.009			
	39 + 9912	8A	0.180			
	Reference Std. #3		0.045			

15	42 + 9191	1A	0.041	0.041		0.041
	42 + 9191	2A	0.055			
	42 + 9191	2B	0.018			
	42 + 9191	2C	0.008			
	42 + 9191	3A	0.096			
	42 + 9191	3B	0.007			
	42 + 9191	3C	0.006			
	42 + 9191	4A	0.050			
	42 + 9191	4B	0.025			
	42 + 9191	5A	0.150			
	42 + 9191	5B	0.054	0.054		0.054
	42 + 9191	5C	0.009			
	42 + 9191	6A	0.170			
	42 + 9191	6B	0.035			
	42 + 9191	6C	0.009			
	42 + 9191	6D	0.011			
	42 + 9191	7A	0.240			
	42 + 9191	7B	0.098			
	42 + 9191	7C	0.012			
	42 + 9191	8A	0.200			
	Reference Std. #3		0.045			
16	45 + 1802	1A	0.024	0.023	0.001	0.024
	45 + 1802	2A	0.019			
	45 + 1802	2B	0.007			
	45 + 1802	2C	0.007			
	45 + 1802	3A	0.033			
	45 + 1802	3B	0.013			
	45 + 1802	3C	0.005			
	45 + 1802	4A	0.043			
	45 + 1802	4B	0.029			
	45 + 1802	5A	0.038			
	45 + 1802	5B	0.007	0.007		0.007
	45 + 1802	5C	0.006			
	45 + 1802	6A	0.083			
	45 + 1802	6B	0.025			
	45 + 1802	6C	0.007			
	45 + 1802	6D	0.005			
	45 + 1802	7A	0.032			
	45 + 1802	7B	0.006			
	45 + 1802	7C	0.007			
	45 + 1802	8A	0.130			
	Reference Std. #3		0.045			

17	53 + 7232	1A	0.052	0.053	0.001	0.053
	53 + 7232	2A	0.044			
	53 + 7232	2B	0.008			
	53 + 7232	2C	0.033			
	53 + 7232	3A	0.095			
	53 + 7232	3B	0.011			
	53 + 7232	3C	0.022			
	53 + 7232	4A	0.050			
	53 + 7232	4B	0.006			
	53 + 7232	5A	0.140			
	53 + 7232	5B	0.042	0.040	0.002	0.041
	53 + 7232	5C	0.077			
	53 + 7232	6A	0.098			
	53 + 7232	6B	0.023			
	53 + 7232	6C	0.057			
	53 + 7232	6D	0.010			
	53 + 7232	7A	0.077			
	53 + 7232	7B	0.010			
	53 + 7232	7C	0.037			
	53 + 7232	8A	0.110			
	Reference Std. #3		0.044			
18	57 + 4722	1A	0.100	0.099	0.001	0.100
	57 + 4722	2A	0.032			
	57 + 4722	2B	0.014			
	57 + 4722	2C	0.007			
	57 + 4722	3A	0.080			
	57 + 4722	3B	0.027			
	57 + 4722	3C	0.018			
	57 + 4722	4A	0.093			
	57 + 4722	4B	0.059			
	57 + 4722	5A	0.180			
	57 + 4722	5B	0.110	0.110		0.110
	57 + 4722	5C	0.037			
	57 + 4722	6A	0.058			
	57 + 4722	6B	0.042			
	57 + 4722	6C	0.024			
	57 + 4722	6D	0.011			
	57 + 4722	7A	0.170			
	57 + 4722	7B	0.150			
	57 + 4722	7C	0.086			
	57 + 4722	8A	0.110			
	Reference Std. #3		0.045			

19	58 + 5501	1A	0.016	0.017	0.001	0.017
	58 + 5501	2A	0.057			
	58 + 5501	2B	0.021			
	58 + 5501	2C	0.009			
	58 + 5501	3A	0.057			
	58 + 5501	3B	0.019			
	58 + 5501	3C	0.023			
	58 + 5501	4A	0.039			
	58 + 5501	4B	0.020			
	58 + 5501	5A	0.180			
	58 + 5501	5B	0.060	0.061	0.001	0.061
	58 + 5501	5C	0.009			
	58 + 5501	6A	0.160			
	58 + 5501	6B	0.035			
	58 + 5501	6C	0.013			
	58 + 5501	6D	0.007			
	58 + 5501	7A	0.220			
	58 + 5501	7B	0.086			
	58 + 5501	7C	0.011			
	58 + 5501	8A	0.240			
	Reference Std. #3		0.044			
20	58 + 5502	1A	0.044	0.044		0.044
	58 + 5502	2A	0.048			
	58 + 5502	2B	0.009			
	58 + 5502	2C	0.008			
	58 + 5502	3A	0.058			
	58 + 5502	3B	0.014			
	58 + 5502	3C	0.010			
	58 + 5502	4A	0.077			
	58 + 5502	4B	0.036			
	58 + 5502	5A	0.110			
	58 + 5502	5B	0.022	0.021	0.001	0.022
	58 + 5502	5C	0.010			
	58 + 5502	6A	0.038			
	58 + 5502	6B	0.010			
	58 + 5502	6C	0.007			
	58 + 5502	6D	0.007			
	58 + 5502	7A	0.056			
	58 + 5502	7B	0.007			
	58 + 5502	7C	0.007			
	58 + 5502	8A	0.130			

	Reference Std. #3		0.045			

Analytical Services

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LEVELTON
Engineering Solutions

QUALITY ASSURANCE/QUALITY CONTROL

Accreditation:

Levelton Analytical Services is a member of the Canadian Association for Environmental Analytical Laboratories (CAEAL). The laboratory is currently certified for a total of 19 inorganic and organic parameters. Levelton also participates in the B.C. Ministry of Environment's Laboratory Proficiency Program and the Asbestos Proficiency Testing Program of the Workers' Compensation Board of B.C.

Analytical Methods and Procedures:

Levelton Analytical Services uses only analytical methodologies that have been approved and refereed by other recognized organizations. These methods have been derived from:

- American Public Health Association-Standard Methods
- U.S. Environmental Protection Agency Methods Manual
- Canadian Society of Soil Science Methods Manual
- British Columbia Environmental Laboratory Manual
- Workers' Compensation Board Laboratory Analytical Methods
- American Society for Testing and Materials Methods
- National Institute of Occupational Safety and Health Methods
- Canadian Standards Association Methods

All analytical methodologies adopted for routine use are evaluated for precision and accuracy using Q.C. samples, duplicates and Certified Reference Standards, when available. Methodologies are reported along with analytical results.

Quality Control Procedures:

- Use of National Institute of Standards (NIST) and other reference standards to measure accuracy.
- Analysis of duplicates to evaluate precision.
- Calibrations for every run and in-line calibration checks.
- Analysis of quality control samples at low and high ends of the linear range.
- Use of method blanks to monitor for contamination.
- Review of final report by Project Chemist and Laboratory Manager.
- Use of Control Charts to track accuracy and bias

Certified by the Canadian Association for Environmental Analytical Laboratories (CAEAL) for specific environmental tests listed in the Registration Status Report

DATE: August 15, 1997

CAEAL PERFORMANCE EVALUATION PROGRAM

PERFORMANCE EVALUATION REPORT

LABORATORY NAME: Levelton Analytical Services
AUDIT DATE: 97.03.31

SAMPLE ID	MATRIX	PARAMETER	UNITS	REFERENCE VALUE	REPORTED VALUE	AD VALUE	(Z SCORE) / 2	POINTS ASSIGNED	PE SCORE
C1-1	WI	ALK	MG/L	88.3	88.4	5.4	0.02	5	
C1-2	WI	ALK	MG/L	11.0	9.9	1.6	-0.69	4	
C1-3	WI	ALK	MG/L	51.5	52.1	3.6	0.17	5	
C1-4	WI	ALK	MG/L	34.9	34.3	2.8	-0.21	5	95
C04B-1	WI	BOD	MG/L	61	43	20	-0.90	4	
C04B-2	WI	BOD	MG/L	15	11	6	-0.67	4	
C04B-3	WI	BOD	MG/L	31	23	11	-0.73	4	
C04B-4	WI	BOD	MG/L	77	59	25	-0.72	4	80
C1-1	WI	CL	MG/L	15.0	15.4	1.4	0.29	5	
C1-2	WI	CL	MG/L	< 0.5	< 2.0	0.5		5	
C1-3	WI	CL	MG/L	45.2	45.3	3.2	0.03	5	
C1-4	WI	CL	MG/L	0.9	< 2.0	0.6		5	100
C1-1	WI	COND	US/CM	272	280	15	0.53	4	
C1-2	WI	COND	US/CM	47	49	3	0.67	4	
C1-3	WI	COND	US/CM	311	312	17	0.06	5	
C1-4	WI	COND	US/CM	98	100	6	0.33	5	90
C1-1	WI	F	MG/L	0.31	0.33	0.08	0.25	5	
C1-2	WI	F	MG/L	0.53	0.58	0.10	0.50	5	
C1-3	WI	F	MG/L	0.77	0.80	0.11	0.27	5	
C1-4	WI	F	MG/L	0.90	0.94	0.12	0.33	5	100
C1-1	WI	NO3	MG/L	0.29	0.22	0.05	-1.40	2	
C1-2	WI	NO3	MG/L	0.74	0.76	0.11	0.18	5	
C1-3	WI	NO3	MG/L	1.24	1.13	0.17	-0.65	4	
C1-4	WI	NO3	MG/L	0.14	0.13	0.04	-0.25	5	80
C1-1	WI	NO3+2	MG/L	0.29	0.22	0.05	-1.40	2	
C1-2	WI	NO3+2	MG/L	0.74	0.76	0.11	0.18	5	
C1-3	WI	NO3+2	MG/L	1.25	1.13	0.17	-0.71	4	
C1-4	WI	NO3+2	MG/L	0.14	0.13	0.04	-0.25	5	80
C15-1	WI	PH	units	2.79	2.77	0.15	-0.13	5	
C15-2	WI	PH	units	5.22	5.19	0.10	-0.30	5	
C15-3	WI	PH	units	7.66	7.62	0.10	-0.40	5	
C15-4	WI	PH	units	8.11	8.11	0.15	0.00	5	100
C1-1	WI	SO4	MG/L	23.8	25.1	2.3	0.57	4	
C1-2	WI	SO4	MG/L	5.7	9.1	0.7	4.86	0	
C1-3	WI	SO4	MG/L	19.6	21.3	2.0	0.85	4	
C1-4	WI	SO4	MG/L	8.7	8.8	1.0	0.10	5	65
C03-1	WI	TP	MG/L	0.059	0.088	0.028	1.04	2	
C03-2	WI	TP	MG/L	0.122	0.138	0.036	0.44	5	
C03-3	WI	TP	MG/L	0.199	0.232	0.046	0.72	4	
C03-4	WI	TP	MG/L	0.325	0.354	0.062	0.47	5	80

LEVELTON
Engineering Solutions

Fax Transmittal

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To: Reid Crowther & Partners Ltd
Att: ~~Mr Paul Carter P.Eng.~~
Fax number: 403 488 2121

cc: Mr Don Hamilton
Fax number:

From: Greg Wennerstrom
Telephone number:

Date: ~~December 10, 1998~~ Apr. 1, 1999
Project number: P98-029

Total number of pages: 13
Please call 403-269-4141 if any pages are missing

Dear Mr Carter

Thank you for your letter ref. 77054-03 dated December 8, 1998 in response to our proposal P98-029 for chloride content analysis of hardened concrete.

We understand that your primary concern in the upcoming Montana DOT study is to obtain accurate chloride analysis test data. We are confident that Levelton Engineering Ltd.'s experience in conducting chloride analysis testing, our participation in laboratory proficiency test programs and the proposed duplicate and reference sample tests will ensure that the test data is accurate.

In reply to your specific questions:

1. "Please define the terms reference and duplicate samples".

A duplicate sample is obtained by splitting a test sample and retaining a portion for subsequent reanalysis or duplicate testing.

A reference sample is a laboratory prepared aqueous solution of known chloride concentration.

2. "Would the retesting be done regardless of whether we supply cores or powder samples?"

Yes, duplicate samples will be tested on either cores or powder samples. If cores are provided the sample slicing and powder preparation fees would be charged.

3. "What is Levelton's policy if the retests are not in agreement with the original test results?

The duplicate test sample results must be within +/_ 10% of the sample test result. If the difference is greater a repeat test is carried out on the retained portion of the test sample. If the repeat test is within +/- 10% of the sample test result no further replicate tests are carried out and the original test result and repeat test result are reported. The duplicate

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result will be reported but identified as an outlier. If the repeat test shows a larger variance, the test procedures and calculations will be reviewed to determine the reason for the variance and duplicate tests may be carried out on the retained portion of all 10 samples in the group.

4."We will likely prefer the acid soluble version on the test method, unless there is a good reason for using the water soluble version. Our proposal to the DOT states that we would use the AASHTO T-260 test method. Could you clarify the difference between the CSA A23.2-4B and the T-260 method.?"

The CSA A23.2-4B method is a test for water soluble chloride ions, and involves boiling the pulverised sample in water which will dissolve water soluble chloride ions in the concrete, including the aggregate. The AASHTO T-260 method is similar to the ASTM C114 method, and uses a nitric acid extraction method which will determine the total chloride content of the concrete and aggregate. The selection of acid soluble or water soluble method will depend on preference or the evaluation of threshold limits for chloride which can be based on either methd.

We are able to carry out chloride tests following the AASHTO T260 or the ASTM C114 method, at the same unit price as indicated in the proposal.

I trust the above clarifies your concerns. Please do not hesitate to contact us should you require further information.

Regards,

GWennerstr

Greg Wennerstrom, P.Eng.

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Bridge No.	Route No.	Features Intersected	Location	Custodian	Type Structure	Deck Wearing Surface
I00090001+ 09821	00090	SEP LOCAL ROAD	3 KM E LOOKOUT PASS	State Hwy Agency	Prestressed Concrete Stringer/Girder	1 Monolithic Concrete
I00090005 + 01481	00090	SEP LOCAL ROAD	13 KM E LOOKOUT PASS	State Hwy Agency	Prestressed Concrete Stringer/Girder	1 Monolithic Concrete
I00090006 + 05481	00090	SEP RANDOLPH CREEK ROAD	6 KM W SALTESE	State Hwy Agency	Prestressed Concrete Stringer/Girder	1 Monolithic Concrete
I00090010 + 01221	00090	ST REGIS RIVER	1 KM W SALTESE	State Hwy Agency	Prestressed Concrete Stringer/Girder	1 Monolithic Concrete
I00090010 + 07441	00090	ST REGIS RIVER	SALTESE	State Hwy Agency	Prestressed Concrete Stringer/Girder	1 Monolithic Concrete
I00090023 + 00631	00090	ST REGIS RIVER, LOCAL RD	7 KM E DE BORGIA	State Hwy Agency	Steel Continuous Stringer/Girder	1 Monolithic Concrete
I00090029 + 02051	00090	ST REGIS RIVER	7 KM W ST. REGIS	State Hwy Agency	Steel Stringer/Girder	1 Monolithic Concrete
I00090029 + 02052	00090	ST REGIS RIVER	7 KM W ST. REGIS	State Hwy Agency	Steel Stringer/Girder	1 Monolithic Concrete
I00090029 + 03682	00090	ST REGIS RIVER	7 KM W ST REGIS	State Hwy Agency	Steel Stringer/Girder	1 Monolithic Concrete
I00090034 + 02081	00090	FRONTAGE ROAD	1 KM E ST. REGIS	State Hwy Agency	Concrete Continuous Slab	1 Monolithic Concrete
I00090034 + 02082	00090	FRONTAGE ROAD	1 KM E ST. REGIS	State Hwy Agency	Concrete Continuous Slab	1 Monolithic Concrete
I00090039 + 08052	00090	CLARK FORK, LOCAL RD	10 KM E ST. REGIS	State Hwy Agency	Steel Continuous Multiple Box Beam	1 Monolithic Concrete
I00090039 + 09911	00090	SEP COUNTY ROAD	10 KM E ST. REGIS	State Hwy Agency	Concrete Continuous Slab	1 Monolithic Concrete
I00090039 + 09912	00090	SEP COUNTY ROAD	10 KM E ST. REGIS	State Hwy Agency	Concrete Continuous Slab	1 Monolithic Concrete
I00090042 + 09191	00090	CLARK FORK	6 KM W SUPERIOR	State Hwy Agency	Steel Continuous Stringer/Girder	1 Monolithic Concrete
I00090058 + 05501	00090	CLARK FORK	17 KM E SUPERIOR	State Hwy Agency	Steel Continuous Girder-Floorbeam	1 Monolithic Concrete
I00090058 + 05502	00090	CLARK FORK	17 KM E SUPERIOR	State Hwy Agency	Steel Continuous Girder-Floorbeam	CONCRETE
I00090045 + 01802	00090	CLARK FORK	4 KM W SUPERIOR	State Hwy Agency	Steel Continuous Girder-Floorbeam	5 Epoxy Overlay
I00090053 + 07232	00090	CLARK FORK	10 KM E SUPERIOR	State Hwy Agency	Steel Continuous Girder-Floorbeam	5 LATEX MODIFIED
I00090057 + 04722	00090	MONTANA RAIL LINK	15 KM E SUPERIOR	State Hwy Agency	Prestressed Concrete Stringer/Girder	5 Epoxy Overlay

$MgCl_2$ & NaCl

NaCl Only

NaCl but
NOT USED IN
COMPARISON

BRIDGE SITES THAT WERE TESTED
IN THIS STUDY

APPENDIX E

MAGNESIUM TREATED BRDIGE SITES

Bridge Sires that Receive $MgCl_2$

Bridge No.	Route No.	Features Intersected	Location	Type Structure	Deck Wearing Surface	Spans	Max Span (m)	Length (m)	Deck Wdth (m)	Deck Area	Year Built	Year Rehab'd	ADT
100015120+06971	00015	LOCAL CREEK RARUS MWR R	2 KM W ROCKER	Steel Stringer/Girder	1 Monolithic Concrete	11	21.336	186.842	9.54	1595	1961	0	5200
100015120+06972	00015	LOCAL CREEK RARUS MWR R	2 KM W ROCKER	Steel Stringer/Girder	1 Monolithic Concrete	11	21.336	182.27	9.54	1556	1961	0	5200
100015122+04231	00015	INT ROCKER	ROCKER	Prestressed Concrete Stringer/Girder	1 Monolithic Concrete	3	13.716	35.966	12.405	417	1968	0	12860
100015122+04232	00015	INT ROCKER	ROCKER	Prestressed Concrete Stringer/Girder	1 Monolithic Concrete	3	14.02	35.966	12.313	417	1968	0	12860
100015124+00371	00015	NEVERSWEAT RAILROAD	3 KM W BUTTE	Concrete Continuous Tee Beam	0 None	3	15.544	40.538	9.662	346	1955	0	15020
100015124+00372	00015	NEVERSWEAT RAILROAD	3 KM W BUTTE	Concrete Continuous Tee Beam	0 None	3	15.544	40.538	9.662	346	1955	0	15020
100015124+06901	00015	SM LOCAL RARUS RAILWAY	2 KM W BUTTE	Prestressed Concrete Stringer Girder	1 Monolithic Concrete	5	19.812	92.049	9.662	786	1964	0	11370
100015124+08262	00015	SM LOCAL RARUS RAILWAY	2 KM W BUTTE	Prestressed Concrete Stringer/Girder	1 Monolithic Concrete	5	19.812	98.145	9.662	838	1964	0	11370
100015124+08701	00015	SILVERBOW CR MT WEST RY	2 KM W BUTTE	Steel Stringer/Girder	1 Monolithic Concrete	7	30.48	134.721	9.022	1150	1964	0	11370
100015125+00842	00015	SILVERBOW CR MT WEST RY	2 KM W BUTTE	Steel Stringer/Girder	1 Monolithic Concrete	8	31.699	149.047	9.022	1272	1964	0	11370
100015125+08831	00015	MONT WESTERN RWY, LOCA	BUTTE	Steel Continuous Stringer Girder	1 Monolithic Concrete	8	22.86	143.865	9.662	1228	1964	0	11370
100015125+08832	00015	MONT WESTERN RWY, LOCA	BUTTE	Steel Stringer/Girder	1 Monolithic Concrete	8	22.86	143.865	9.662	1228	1964	0	11370
100015126+03161	00015	INT MONTANA STREET	BUTTE	Steel Stringer/Girder	1 Monolithic Concrete	3	23.469	51.205	9.631	437	1961	0	11370
100015126+03162	00015	INT MONTANA STREET	BUTTE	Steel Stringer/Girder	1 Monolithic Concrete	3	23.469	51.206	9.662	437	1961	0	11370
100015127+09361	00015	INT HARRISON AVE	BUTTE	Prestressed Concrete Stringer/Girder	1 Monolithic Concrete	4	18.288	63.703	9.631	544	1960	0	12210
100015127+09362	00015	INT HARRISON AVE	BUTTE	Prestressed Concrete Stringer/Girder	1 Monolithic Concrete	4	18.592	63.703	9.631	544	1960	0	12210
100015130+00261	00015	BNRR (TRACKS NOT IN USE)	BUTTE	Prestressed Concrete Stringer/Girder	1 Monolithic Concrete	4	21.64	66.751	12.588	773	1986	0	3100
100015130+00262	00015	BNRR (TRACKS NOT IN USE)	BUTTE	Steel Stringer/Girder	1 Monolithic Concrete	4	23.469	70.104	14.325	940	1966	0	3100
100015192+06941	00015	U5806 MONTANA RAIL LINK	HELENA	Steel Continuous Stringer/Girder	1 Monolithic Concrete	12	53.949	243.84	9.692	2081	1961	0	15100
100015192+06942	00015	U5806 MONTANA RAIL LINK	HELENA	Steel Continuous Girder-Floorbeam	1 Monolithic Concrete	12	53.949	247.497	9.692	2112	1961	0	15100
100015357+00751	00015	MARIAS RIVER	9 KM S SHELBY	Prestressed Concrete Stringer/Girder	1 Monolithic Concrete	5	38.404	147.523	13.472	1866	1976	0	2690
100015357+00752	00015	MARIAS RIVER	9 KM S SHELBY	Prestressed Concrete Stringer/Girder	1 Monolithic Concrete	5	38.404	147.523	13.472	1866	1976	0	2690
100015363+04831	00015	INT SHELBY BN RR	SHELBY	Steel Stringer/Girder	6 Bituminous	8	20.421	130.759	13.319	1594	1960	1993	2080
100015363+04832	00015	INT SHELBY BN RR	SHELBY	Steel Stringer/Girder	6 Bituminous	8	20.421	130.759	9.662	1116	1960	1993	2080
100015379+02551	00015	INT KEVIN	17 KM S SUNBURST	Prestressed Concrete Stringer/Girder	1 Monolithic Concrete	3	21.945	43.891	13.38	574	1980	0	1870
100015379+02552	00015	INT KEVIN	17 KM S SUNBURST	Prestressed Concrete Stringer/Girder	1 Monolithic Concrete	3	14.02	36.576	14.569	501	1964	0	1870
100015389+08151	00015	INT SUNBURST	SUNBURST	Prestressed Concrete Stringer/Girder	1 Monolithic Concrete	3	19.812	44.805	13.472	560	1977	0	1810
100015389+08152	00015	INT SUNBURST	SUNBURST	Prestressed Concrete Stringer/Girder	6 Bituminous	3	19.812	51.816	9.723	442	1961	0	1810
100090001+09821	00090	SEP LOCAL ROAD	3 KM E LOOKOUT PASS	Prestressed Concrete Stringer/Girder	1 Monolithic Concrete	3	17.068	48.463	25.786	1188	1973	0	5710
100090005+01481	00090	SEP LOCAL ROAD	13 KM E LOOKOUT PASS	Prestressed Concrete Stringer/Girder	1 Monolithic Concrete	3	31.089	94.488	25.786	2316	1973	0	5710
100090005+06861	00090	INT TAFT	15 KM E LOOKOUT PASS	Prestressed Concrete Stringer/Girder	1 Monolithic Concrete	3	18.592	40.538	25.786	993	1973	0	5710
100090006+05481	00090	SEP RANDOLPH CREEK ROAD	6 KM W SALTESE	Prestressed Concrete Stringer/Girder	1 Monolithic Concrete	3	14.02	35.966	25.786	881	1973	0	5710
100090010+01221	00090	ST REGIS RIVER	1 KM W SALTESE	Prestressed Concrete Stringer/Girder	1 Monolithic Concrete	3	21.945	46.939	25.359	1150	1973	[illegible]	5710
100090010+05291	00090	INT SALTESE	SALTESE	Prestressed Concrete Stringer/Girder	1 Monolithic Concrete	3	22.8	22.8	25	585	1973	0	5710
100090010+07441	00090	ST REGIS RIVER	SALTESE	Prestressed Concrete Stringer/Girder	1 Monolithic Concrete	3	23.164	60.35	27.492	1479	1973	0	6050
100090016+03301	00090	INT HAUGAN	HAUGAN	Concrete Continuous Tee Beam	0 None	3	24.688	35.661	13.716	468	1976	0	6050
100090016+03302	00090	INT HAUGAN	HAUGAN	Concrete Continuous Tee Beam	0 None	3	24.688	35.661	13.716	460	1976	0	6050
100090018+09271	00090	INT DEBORGIA	DE BORGIA	Prestressed Concrete Stringer/Girder	1 Monolithic Concrete	3	17.373	36.576	13.776	474	1976	0	6050
100090018+09272	00090	INT DEBORGIA	DE BORGIA	Prestressed Concrete Stringer Girder	1 Monolithic Concrete	3	17.373	36.576	13.776	474	1976	0	6050
100090022+00131	00090	INT HENDERSON	5 KM E DE BORGIA	Prestressed Concrete Stringer/Girder	1 Monolithic Concrete	3	17.068	42.062	27.919	1097	1980	0	5270
100090023+00631	00090	ST REGIS RIVER, LOCAL RD	7 KM E DE BORGIA	Steel Continuous Stringer/Girder	1 Monolithic Concrete	3	53.34	138.684	26.791	3618	1979	0	5270
100090023+03251	00090	ST REGIS RIVER, LOCAL RD	7 KM E DE BORGIA	Steel Continuous Stringer/Girder	1 Monolithic Concrete	4	54.559	194.462	26.791	5074	1679	0	5270
100090024+04051	00090	ST REGIS RIVER	9 KM E DE BORGIA	Prestressed Concrete Stringer/Girder	1 Monolithic Concrete	4	29.565	116.128	13.289	1472	1980	0	5270
100090024+06031	00090	ST REGIS RIVER	9 KM E DE BORGIA	Prestressed Concrete Stringer/Girder	1 Monolithic Concrete	4	31.089	122.529	13.289	1554	1980	0	5270
100090025+03931	00090	INT DREXEL	10 KM E DE BORGIA	Prestressed Concrete Stringer/Girder	1 Monolithic Concrete	3	14.02	37.49	13.289	475	1980	0	5270
100090025+03932	00090	INT DREXEL	10 KM E DE BORGIA	Prestressed Concrete Stringer/Girder	1 Monolithic Concrete	3	14.02	37.49	13.289	475	1980	0	5270
100090029+02051	00090	ST REGIS RIVER	7 KM W ST REGIS	Steel Stringer/Girder	1 Monolithic Concrete	[illegible]	31.089	122.63	13.045	1769	1981	0	5270
100090029+02052	00090	ST REGIS RIVER	7 KM W ST REGIS	Steel Stringer/Girder	1 Monolithic Concrete	4	31.089	122.529	13.045	1419	1981	0	5270
100090029+03681	00090	ST REGIS RIVER	7 KM W ST REGIS	Steel Stringer/Girder	1 Monolithic Concrete	[illegible]	36.88	133.5	13.045	1546	1981	0	5270
100090029+03682	00090	ST REGIS RIVER	7 KM W ST REGIS	Steel Stringer/Girder	1 Monolithic Concrete	[illegible]	36.88	118.262	13.045	1370	1981	0	5270
100090030+01171	00090	INT TWO MILE-ST REGIS RV	6 KM W ST REGIS	Prestressed Concrete Stringer/Girder	1 Monolithic Concrete	3	30.784	86.868	13.228	1096	1981	0	5270
100090030+01172	00090	INT TWO MILE-ST REGIS RV	6 KM W ST. REGIS	Prestressed Concrete Stringer/Girder	1 Monolithic Concrete	3	30.784	86.868	13.228	1096	1981	0	5270
100090030+02024	00090	ST REGIS RIVER-INT RAMP	6 KM W ST REGIS	Concrete Tee Beam	0 None	2	23.164	45.72	8.839	385	1981	0	5270
100090030+05492	00090	ST REGIS RIVER	5 KM W ST REGIS	Steel Continuous Stringer/Girder	1 Monolithic Concrete	4	30.784	114.604	13.106	1453	1981	0	5270
100090031+04741	00090	ST REGIS RIVER	3 KM W ST REGIS	Prestressed Concrete Stringer/Girder	1 Monolithic Concrete	2	32.308	64.617	13.228	815	1981	0	5270
100090033+04071	00090	INT ST REGIS	ST REGIS	Prestressed Concrete Stringer/Girder	1 Monolithic Concrete	3	15.24	38.1	13.441	512	1983	0	5270
100090033+04072	00090	INT ST REGIS	ST REGIS	Prestressed Concrete Stringer/Girder	1 Monolithic Concrete	3	15.24	38.1	13.441	480	1983	0	5270
100090033+05281	00090	ST REGIS RIVER	ST REGIS	Prestressed Concrete Stringer/Girder	1 Monolithic Concrete	3	24.384	74.98	13.441	944	1983	0	6220
100090033+05282	00090	ST REGIS RIVER	ST REGIS	Prestressed Concrete Stringer/Girder	1 Monolithic Concrete	3	24.384	74.98	13.441	944	1983	0	6220
100090033+05283	00090	ST REGIS RIVER-INT RAMP	ST REGIS	Prestressed Concrete Stringer/Girder	1 Monolithic Concrete	3	25.908	80.162	12.222	911	1983	0	6220
100090033+05284	00090	ST REGIS RIVER-INT RAMP	ST REGIS	Prestressed Concrete Stringer/Girder	1 Monolithic Concrete	3	21.945	64.008	9.174	535	1983	0	6220
100090061+07931	00090	INT TARKIO COUNTY ROAD	22 KM W ALBERTON	Prestressed Concrete Stringer/Girder	5 Epoxy Overlay	3	14.02	39.624	12.405	459	1959	0	6720
100090061+07932	00090	INT TARKIO COUNTY ROAD	22 KM W ALBERTON	Prestressed Concrete Stringer/Girder	5 Epoxy Overlay	3	14.02	39.624	12.405	492	1959	0	6720
100090065+04971	00090	SEP COUNTY ROAD	16 KM W ALBERTON	Prestressed Concrete Stringer/Girder	5 Epoxy Overlay	[illegible]	40.538	136.55	13.411	1582	1981	[illegible]	6720
100090065+04972	00090	SEP COUNTY ROAD	16 KM W ALBERTON	Steel Continuous Stringer/Girder	5 Epoxy Overlay	8	17.068	135.94	9.509	1160	1965	0	6720
100090066+02791	00090	CLARK FORK	15 KM W ALBERTON	Steel Continuous Stringer/Girder	1 Monolithic Concrete	5	57.912	264.261	13.533	3335	1981	0	6720
100090066+02792	00090	CLARK FORK	15 KM W ALBERTON	Steel Continuous Girder Floorbeam	5 Epoxy Overlay	7	64.008	245.973	9.601	2099	1965	0	6720
100090066+04211	00090	MONTANA RAIL LINK	15 KM W ALBERTON	Prestressed Concrete Stringer/Girder	1 Monolithic Concrete	4	32.918	100.279	13.533	1265	1981	0	6720
100090066+04212	00090	MONTANA RAIL LINK	15 KM W ALBERTON	Steel Stringer/Girder	5 Epoxy Overlay	7	15.544	103.327	9.692	882	1965	0	6720
100090069+00411	00090	LOCAL MONTANA RAIL LINK	10 KM W ALBERTON	Prestressed Concrete Stringer/Girder	1 Monolithic Concrete	4	17.373	60.96	12.618	706	1981	0	6720
100090069+00412	00090	LOCAL, MONTANA RAIL LINK	10 KM W ALBERTON	Prestressed Concrete Stringer/Girder	1 Monolithic Concrete	4	18.897	57.912	14.264	777	1964	0	6720
100090070+00901	00090	INT CYR CLARK FORK	8 KM W ALBERTON	Steel Continuous Stringer/Girder	1 Monolithic Concrete	7	51.206	238.048	13.533	3004	1981	0	6980
100090070+00902	00090	INT CYR CLARK FORK	8 KM W ALBERTON	Steel Continuous Girder-Floorbeam	1 Monolithic Concrete	[illegible]	50.596	232.257	9.692	1982	1965	0	6980
100090077+06411	00090	INT LOTHROP	4 KM E ALBERTON	Prestressed Concrete Stringer/Girder	1 Monolithic Concrete	3	18.288	43.586	13.472	551	1975	0	5880
100090077+06412	00090	INT LOTHROP	4 KM E ALBERTON	Prestressed Concrete Stringer/Girder	1 Monolithic Concrete	3	12.192	37.49	14.295	503	1963	0	5880
100090079+04271	00090	SEP COUNTY ROAD	7 KM E ALBERTON	Concrete Slab	1 Monolithic Concrete	1	4.876	5.486	36	74	1963	1979	5880
100090080+03411	00090	CLARK FORK	8 KM E ALBERTON	Steel Continuous Stringer/Girder	5 Epoxy Overlay	7	46.329	310.896	13.289	3942	1979	0	5880
100090080+03412	00090	CLARK FORK	8 KM E ALBERTON	Steel Continuous Girder-Floorbeam	5 Epoxy Overlay	7	46.329	267.919	8.991	2287	1964	0	5880
100090081+08401	00090	CLARK FORK RIVER	10 KM E ALBERTON	Steel Continuous Girder-Floorbeam	5 Epoxy Overlay	9	48.768	299.313	18.989	5109	1964	0	5880
100090082+06231	00090	INT NINE MILE	11 KM W FRENCHTOWN	Prestressed Concrete Stringer/Girder	5 Epoxy Overlay	3	12.496	37.795	11.734	432	1964	0	7200
100090082+06232	00090	INT NINE MILE	11 KM W FRENCHTOWN	Prestressed Concrete Stringer/Girder	5 Epoxy Overlay	3	12.496	37.795	11.734	432	1964	0	7200
100090086+06411	00090	SEP HOULE CREEK ROAD	5 KM W FRENCHTOWN	Concrete Continuous Slab	1 Monolithic Concrete	3	9.144	24.079	13.228	304	1971	0	7200
100090086+06412	00090	SEP HOULE CREEK ROAD	5 KM W FRENCHTOWN	Concrete Continuous Slab	1 Monolithic Concrete	3	9.144	24.079	13.228	304	1971	0	7200
100090093+03971	00090	SEP COUNTY ROAD	6 KM E FRENCHTOWN	Concrete Continuous Slab	1 Monolithic Concrete	3	9.144	24.079	13.228	304	1971	0	9040
100090093+03972	00090	SEP COUNTY ROAD	6 KM E FRENCHTOWN	Concrete Continuous Slab	1 Monolithic Concrete	3	9.144	24.079	13.228	304	1971	0	9040
100090096+09851	00090	MONTANA RAIL LINK	8 KM W MISSOULA	Prestressed Concrete Stringer/Girder	1 Monolithic Concrete	3	17.068	49.682	11.887	569	1966	0	16350
100090096+09852	00090	MONTANA RAIL LINK	8 KM W MISSOULA	Prestressed Concrete Stringer/Girder	1 Monolithic Concrete	3	17.068	49.682	11.887	569	1966	1986	16350
100090098+04271	00090	SEP COUNTY ROAD	6 KM W MISSOULA	Prestressed Concrete Stringer/Girder	1 Monolithic Concrete	3	15.849	42.062	12.192	477	1966	0	16350
100090098+04272	00090	SEP COUNTY ROAD	6 KM W MISSOULA	Prestressed Concrete Stringer/Girder	1 Monolithic Concrete	3	15.849	42.062	12.192	477	1966	0	16350
100090101+07081	00090	INT RESERVE STREET	MISSOULA	Prestressed Concrete Stringer/Girder	1 Monolithic Concrete	4	15.849	59.436	12.192	674	1966	1986	17070
100090101+07082	00090	INT RESERVE STREET	MISSOULA	Prestressed Concrete Stringer/Girder	1 Monolithic Concrete	4	15.849	59.436	12.192	674	1966	0	17070
100090101+07083	00090	GRANT CREEK INT RAMP	MISSOULA	Concrete Slab	1 Monolithic Concrete	1	9.753	9.753	8.229	71	1966	[illegible]	17070
100090101+07084	00090	GRANT CREEK-INT RAMP	MISSOULA	Concrete Slab	1 Monolithic Concrete	1	9.753	9.753	8.229	71	1966	0	17070
100090103+01641	00090	SEP COUNTY ROAD	MISSOULA	Prestressed Concrete Stringer/Girder	1 Monolithic Concrete	3	15.849	42.062	12.313	477	1966	0	17070
100090103+01642	00090	SEP COUNTY ROAD	MISSOULA	Prestressed Concrete Stringer/Girder	1 Monolithic Concrete	3	15.849	42.062	12.313	477	1966	0	17070
100090104+07801	00090	INT ORANGE STREET	MISSOULA	Prestressed Concrete Stringer/Girder	1 Monolithic Concrete	3	21.945	54.559	11.765	609	1966	0	17200
100090104+07802	00090	INT ORANGE STREET	MISSOULA	Prestressed Concrete Stringer/Girder	1 Monolithic Concrete	3	21.945	54.559	11.765	609	1966	0	17200
100090105+04671	00090	DUNCAN DR RATTLESNAKE C	MISSOULA	Prestressed Concrete Stringer/Girder	1 Monolithic Concrete	4	31.089	74.676	11.43	842	1966	0	19330
100090105+04672	00090	DUNCAN DR RATTLESNAKE C	MISSOULA	Prestressed Concrete Stringer/Girder	1 Monolithic Concrete	4	31.089	74.676	14.02	1024	1966	0	19330
100090105+04673	00090	RATTLESNAKE ST-INT RAMP	MISSOULA	Prestressed Concrete Stringer/Girder	1 Monolithic Concrete	4	25.908	68.58	7.315	481	1966	0	19330
100090105+06331	00090	INT VAN BUREN STREET	MISSOULA	Prestressed Concrete Stringer/Girder	1 Monolithic Concrete	4	12.801	50.292	12.039	583	1964	0	19330
100090105+06332	00090	INT VAN BUREN STREET	MISSOULA	Prestressed Concrete Stringer/Girder	1 Monolithic Concrete	4	12.801	50.292	12.039	583	1964	0	19330
100090107+02701	00090	INT E MISSOULA	EAST MISSOULA	Prestressed Concrete Stringer/Girder	1 Monolithic Concrete	3	21.945	59.131	12.039	670	1964	0	17990
100090107+02702	00090	INT E MISSOULA	EAST MISSOULA	Prestressed Concrete Stringer/Girder	1 Monolithic Concrete	3	21.945	59.131	12.039	670	1964	0	17990
100090175+02151	00090	LITTLE BLACKFOOT RIVER	2 KM S GARRISON	Prestressed Concrete Stringer/Girder	1 Monolithic Concrete	2	19.812	39.928	13.898	506	1979	0	7430
100090175+02152	00090	LITTLE BLACKFOOT RIVER	2 KM S GARRIOSN	Prestressed Concrete Stringer/Girder	1 Monolithic Concrete	2	19.812	39.928	13.898	506	1979	0	7430
100090175+05331	00090	INT E GARRISON MT W RY	2 KM S GARRISON	Steel Continuous Stringer/Girder	5 Epoxy Overlay	5	45.11	182.27	13.38	2306	1979	0	7430
100090175+05332	00090	INT E GARRISON MT W RY	2 KM S GARRISON	Steel Continuous Stringer/Girder	5 Epoxy Overlay	5	45.11	177.393	13.38	2244	1979	0	7430
100090195+07131	00090	ABANDONED RAILROAD	15 KM S DEER LODGE	Steel Continuous Stringer/Girder	1 Monolithic Concrete	3	46.634	120.091	13.472	1519	1978	0	6580
100090195+07132	00090	ABANDONED RAILROAD	15 KM S DEER LODGE	Steel Continuous Stringer/Girder	1 Monolithic Concrete	3	46.634	118.567	13.38	1500	1978	0	6580
100090227+04551	00090	INT I-15	BUTTE	Steel Stringer/Girder	1 Monolithic Concrete	3	23.164	58.826	12.374	681	1963	0	7900
100090227+04552	00090	INT I 15	BUTTE	Steel Stringer/Girder	1 Monolithic Concrete	3	23.164	59.131	12.496	685	1963	0	7900
100090290+07391	00090	CAMP CREEK	3 KM E MANHATTAN	Prestressed Concrete Stringer/Girder	1 Monolithic Concrete	2	12.496	25.298	11.978	288	1965	0	9080
100090290+07392	00090	CAMP CREEK	3 KM E MANHATTAN	Prestressed Concrete Stringer/Girder	1 Monolithic Concrete	2	12.496	25.298	11.978	288	1965	0	9080
100090290+09511	00090	BAKER CREEK	3 KM E MANHATTAN	Prestressed Concrete Stringer/Girder	1 Monolithic Concrete	2	14.02	28.346	11.978	322	1965	0	9080
100090290+09512	00090	BAKER CREEK	3 KM E MANHATTAN	Prestressed Concrete Stringer/Girder	1 Monolithic Concrete	2	14.02	28.346	11.978	322	1965	0	9080
100090291+06371	00090	SEP HEEB LANE	4 KM E MANHATTAN	Prestressed Concrete Stringer/Girder	1 Monolithic Concrete	3	12.801	35.052	11.978	399	1965	0	9080
100090291+06372	00090	SEP HEEB LANE	4 KM E MANHATTAN	Prestressed Concrete Stringer/Girder	1 Monolithic Concrete	3	12.801	35.052	11.978	399	1965	0	9080
100090292+04251	00090	GALLATIN RIVER	5 KM E MANHATTAN	Prestressed Concrete Stringer/Girder	5 Epoxy Overlay	4	15.849	62.788	11.978	714	1965	0	9080
100090292+04252	00090	GALLATIN RIVER	5 KM E MANHATTAN	Prestressed Concrete Stringer/Girder	5 Epoxy Overlay	4	15.24	62.788	11.978	714	1965	0	9080
100090293+02131	00090	SEP CENTRAL PARK	8 KM W BELGRADE	Prestressed Concrete Stringer/Girder	1 Monolithic Concrete	3	12.192	34.747	12.496	402	1965	0	9080
100090293+02132	00090	SEP CENTRAL PARK	8 KM W BELGRADE	Prestressed Concrete Stringer/Girder	1 Monolithic Concrete	3	12.192	34.747	12.496	402	1965	0	9080
100090303+05881	00090	SEP VALLEY CENTER ROAD	4 KM W BOZEMAN	Prestressed Concrete Stringer Girder	1 Monolithic Concrete	3	12.192	34.747	12.496	402	1966	0	16580
100090303+05882	00090	SEP VALLEY CENTER ROAD	4 KM W BOZEMAN	Prestressed Concrete Stringer/Girder	1 Monolithic Concrete	3	12.192	34.747	12.496	402	1966	0	16580
100090307+06281	00090	P 86 MONT RAIL LINK	BOZEMAN	Steel Continuous Stringer/Girder	1 Monolithic Concrete	3	41.452	109.423	12.496	1267	1968	1981	11860
100090307+06282	00090	P 86 MONT RAIL LINK	BOZEMAN	Steel Continuous Stringer/Girder	1 Monolithic Concrete	3	41.452	109.423	12.496	1267	1968	1981	11860
100090307+08431	00090	MONTANA RAIL LINK	BOZEMAN	Prestressed Concrete Stringer/Girder	1 Monolithic Concrete	3	21.64	57.912	12.496	671	1968	0	11860
100090307+08432	00090	MONTANA RAIL LINK	BOZEMAN	Prestressed Concrete Stringer/Girder	1 Monolithic Concrete	3	21.64	57.912	12.496	671	1968	0	11860

I00090308+00001	00090	SEP L STREET	BOZEMAN	Prestressed Concrete Stringer/Girder	1 Monolithic Concrete	3	18.897	44.196	12.496	512	1968	0	11860
I00090308+00002	00090	SEP L STREET	BOZEMAN	Prestressed Concrete Stringer/Girder	1 Monolithic Concrete	3	18.897	44.196	12.496	512	1968	0	11860
I00090309+00591	00090	MONTANA RAIL LINK	BOZEMAN	Steel Continuous Stringer/Girder	1 Monolithic Concrete	3	35.052	92.964	13.472	1176	1971	0	10840
I00090309+00592	00090	MONTANA RAIL LINK	BOZEMAN	Steel Continuous Stringer/Girder	1 Monolithic Concrete	3	35.052	92.964	14.386	1261	1971	0	10840
I00090309+03701	00090	INT EAST BOZEMAN-P 50	BOZEMAN	Prestressed Concrete Stringer/Girder	1 Monolithic Concrete	4	20.421	62.788	12.405	727	1971	0	10840
I00090309+03702	00090	INT EAST BOZEMAN-P 50	BOZEMAN	Prestressed Concrete Stringer/Girder	1 Monolithic Concrete	4	20.421	62.788	13.959	823	1971	0	10840
I00090434+00901	00090	INT LAUREL-P 4, BN RAIL	LAUREL	Steel Stringer/Girder	1 Monolithic Concrete	5	34.137	111.556	9.723	952	1964	0	12980
I00090434+00902	00090	INT LAUREL-P 4, BN RAIL	LAUREL	Steel Stringer/Girder	1 Monolithic Concrete	5	34.137	111.556	13.38	1471	1964	1981	12980
I00090437+04791	00090	INT MOSSMAIN ROAD-P 4	5 KM E LAUREL	Prestressed Concrete Stringer/Girder	1 Monolithic Concrete	3	14.325	36.576	12.496	424	1964	0	17950
I00090437+04792	00090	INT MOSSMAIN ROAD-P 4	5 KM E LAUREL	Prestressed Concrete Stringer/Girder	1 Monolithic Concrete	3	14.325	36.576	12.496	424	1964	0	17950
I00090438+00391	00090	BBWA CANAL	6 KM E LAUREL	Prestressed Concrete Stringer/Girder	6 Bituminous	1	12.192	12.496	12.649	145	1964	0	17950
I00090438+00392	00090	BBWA CANAL	6 KM E LAUREL	Prestressed Concrete Stringer/Girder	6 Bituminous	1	12.192	12.496	12.649	145	1964	0	17950
I00090440+02531	00090	SEP COUNTY ROAD	9 KM W BILLINGS	Prestressed Concrete Stringer/Girder	6 Bituminous	3	18.897	46.634	9.631	398	1961	0	17950
I00090440+02532	00090	SEP COUNTY ROAD	9 KM W BILLINGS	Prestressed Concrete Stringer/Girder	6 Bituminous	3	18.897	46.634	9.631	398	1961	0	17950
I00090442+08261	00090	CANYON CREEK	5 KM W BILLINGS	Prestressed Concrete Stringer/Girder	6 Bituminous	3	15.849	46.634	9.692	398	1959	0	17950
I00090442+08262	00090	CANYON CREEK	5 KM W BILLINGS	Prestressed Concrete Stringer/Girder	6 Bituminous	3	15.849	46.634	9.448	398	1959	0	17950
I00090445+04541	00090	HOGAN SLOUGH	BILLINGS	Prestressed Concrete Stringer/Girder	6 Bituminous	2	12.496	24.993	12.679	289	1959	0	17680
I00090445+04542	00090	HOGAN SLOUGH	BILLINGS	Prestressed Concrete Stringer/Girder	6 Bituminous	2	12.496	24.993	12.679	289	1959	0	17680
I00090445+09641	00090	INT W BILLINGS-U1020	BILLINGS	Prestressed Concrete Stringer/Girder	5 Epoxy Overlay	4	15.849	56.388	12.649	653	1964	0	17680
I00090445+09642	00090	INT W BILLINGS-U1020	BILLINGS	Prestressed Concrete Stringer/Girder	5 Epoxy Overlay	4	15.849	56.388	12.649	653	1964	0	17680
I00090446+01581	00090	INT W BILLINGS-U1010	BILLINGS	Steel Continuous Stringer/Girder	1 Monolithic Concrete	1	42.976	43.586	12.283	496	1994	0	17680
I00090446+01582	00090	INT W BILLINGS-U1010	BILLINGS	Steel Continuous Stringer/Girder	1 Monolithic Concrete	1	42.672	43.586	12.283	496	1994	0	17680
I00090448+04001	00090	IRRIGATION DITCH	BILLINGS	Steel Culvert	1 Monolithic Concrete	2	3.048	7.01	0	83	1966	0	17680
I00090450+05271	00090	MT POWER RR SPUR	BILLINGS	Prestressed Concrete Stringer/Girder	5 Epoxy Overlay	3	15.849	45.11	12.222	509	1966	0	14460
I00090450+05272	00090	MT POWER RR SPUR	BILLINGS	Prestressed Concrete Stringer/Girder	5 Epoxy Overlay	3	15.849	45.11	12.222	509	1966	0	14460
I00090452+00331	00090	YELLOWSTONE RIVER	BILLINGS	Steel Continuous Girder-Floorbeam	5 Epoxy Overlay	9	55.778	288.036	9.631	2458	1962	0	14810
I00090452+00332	00090	YELLOWSTONE RIVER	BILLINGS	Steel Continuous Girder-Floorbeam	5 Epoxy Overlay	9	55.778	288.036	9.631	2458	1962	0	14810
I00090455+03081	00090	INT JOHNSON LANE (U1028)	4 KM E BILLINGS	Prestressed Concrete Stringer/Girder	1 Monolithic Concrete	3	17.373	46.634	12.192	526	1967	0	13450
I00090455+03082	00090	INT JOHNSON LANE (U1028)	4 KM E BILLINGS	Prestressed Concrete Stringer/Girder	1 Monolithic Concrete	3	17.373	45.72	12.192	516	1967	0	13450
I00094138+03301	00094	INT P-18 (MT 59)	MILES CITY	Prestressed Concrete Stringer/Girder	1 Monolithic Concrete	3	20.116	48.158	9.662	411	1961	0	3640
I00094138+03302	00094	INT P-18 (MT 59)	MILES CITY	Prestressed Concrete Stringer/Girder	1 Monolithic Concrete	3	23.164	51.511	13.411	652	1974	0	3640
I00094140+06631	00094	JR GRADE SEP	2 KM E MILES CITY	Concrete Slab	6 Bituminous	1	4.267	4.267	37.764	114	1962	1974	3640
I00094214+08321	00094	YELLOWSTONE RIVER	GLENDIVE	Steel Continuous Girder-Floorbeam	1 Monolithic Concrete	10	82.296	601.37	9.448	5132	1968	0	3180
I00094214+08322	00094	YELLOWSTONE RIVER	GLENDIVE	Steel Continuous Girder-Floorbeam	1 Monolithic Concrete	10	82.296	613.562	9.448	5236	1968	0	3180
I00315000+00001	00315	INT I-15	GREAT FALLS	Prestressed Concrete Stringer/Girder	5 Epoxy Overlay	5	21.336	89.611	16.459	1229	1967	1995	12900
I00315000+03421	00315	FAU 5225-BRIDGE ST	GREAT FALLS	Prestressed Concrete Stringer/Girder	1 Monolithic Concrete	3	15.849	45.72	11.948	518	1967	1995	12900
I00315000+03422	00315	FAU 5225-BRIDGE ST	GREAT FALLS	Prestressed Concrete Stringer/Girder	1 Monolithic Concrete	3	15.849	44.196	11.948	603	1967	1995	12900
I00315001+00691	00315	BN RAILROAD	GREAT FALLS	Steel Continuous Stringer/Girder	1 Monolithic Concrete	3	20.421	54.254	10.515	496	1946	1996	15850
I00315001+00692	00315	BN RAILROAD	GREAT FALLS	Steel Stringer/Girder	1 Monolithic Concrete	5	15.849	63.398	10.119	580	1967	1996	15850
P00001014+05731	00002	CALLAHAN CREEK	TROY	Prestressed Concrete Stringer/Girder	1 Monolithic Concrete	2	25.603	51.511	14.325	691	1989	0	4190
P00001031+01281	00002	PARMENTER CREEK	1M NW LIBBY	Concrete Slab	6 Bituminous	1	7.924	7.924	21.244	164	1970	0	6720
P00001032+00381	00002	FLOWER CREEK	LIBBY	Concrete Slab	6 Bituminous	1	7.924	7.924	22.89	164	1970	0	8670
P00001035+02771	00002	BIG CHERRY CREEK	3M SW LIBBY	Prestressed Concrete Stringer/Girder	1 Monolithic Concrete	2	22.86	46.024	25.054	954	1976	0	6890
P00001122+03341	00002	STILLWATER RIVER	1M NE KALISPELL	Prestressed Concrete Stringer/Girder	1 Monolithic Concrete	2	27.736	56.083	10.058	513	1966	1995	31450
P00001122+03342	00002	STILLWATER RIVER	1M NE KALISPELL	Prestressed Concrete Stringer/Girder	1 Monolithic Concrete	2	27.736	56.083	10.058	513	1966	1995	31450
P00001137+03441	00002	FLATHEAD RIVER	COLUMBIA FALLS	Prestressed Concrete Stringer/Girder	1 Monolithic Concrete	4	36.576	148.132	30.022	3973	1977	0	10090
P00001142+02631	00002	SO. FORK FLATHEAD RIVER	HUNGRY HORSE	Steel Continuous Girder-Floorbeam	1 Monolithic Concrete	7	41.757	180.441	8.869	1430	1938	0	6300
P00001353+08951	00002	SAGE CREEK	GILDFORD	Concrete Continuous Tee Beam	6 Bituminous	4	13.716	36.576	9.662	312	1958	0	1060
P00001376+02951	00002	BIG SANDY CREEK	5M W HAVRE	Concrete Continuous Tee Beam	0 None	4	17.678	44.5	9.448	380	1954	0	3140
P00001378+00911	00002	BN RAILROAD	3M W HAVRE	Steel Continuous Stringer/Girder	1 Monolithic Concrete	5	27.432	95.402	9.662	814	1960	0	3140
P00001397+07721	00002	MILK RIVER	6M W CHINOOK	Steel Truss-Thru	1 Monolithic Concrete	2	36.576	74.676	7.772	546	1938	0	2450
P00001401+07921	00002	DRAINAGE	2M W CHINOOK	Wood or Timber Stringer/Girder	6 Bituminous	2	5.791	11.887	9.174	101	1938	0	2450
P00001413+08451	00002	FIFTEEN MILE CREEK	1M E ZURICH	Steel Continuous Stringer/Girder	6 Bituminous	2	16.459	33.832	9.784	289	1949	0	2010
P00001425+06901	00002	MAIN IRRIGATION CANAL	HARLEM	Concrete Slab	6 Bituminous	1	7.62	7.62	12.801	93	1968	0	3380
P00001427+09391	00002	MILK RIVER	FORT BELNAP AGENCY	Prestressed Concrete Stringer/Girder	1 Monolithic Concrete	3	21.945	65.227	9.753	561	1964	0	3380
P00001442+08001	00002	WHITE BEAR CREEK	11M W DODSON	Prestressed Concrete Stringer/Girder	1 Monolithic Concrete	3	13.716	41.757	12.893	509	1993	0	1130
P00002000+00001	00094	INT W MILES CITY-I 94	3M SW MILES CITY	Steel Stringer/Girder	6 Bituminous	4	23.774	81.686	9.083	697	1961	0	1370
P00002000+08791	00094	BN RAILROAD	2M SW MILES CITY	Steel Stringer/Girder	6 Bituminous	6	19.202	94.792	9.052	809	1954	0	1370
P00002002+02721	00094	TONGUE RIVER	MILES CITY	Steel Continuous Girder-Floorbeam	1 Monolithic Concrete	3	34.747	91.44	10.607	613	1934	0	5300
P00005000+00001	00093	INT DESMET I-90	5M NW MISSOULA	Prestressed Concrete Stringer/Girder	3 Latex Concrete/Simil	4	29.3	105.5	8.793	927	1966	1995	7980
P00005061+01811	00093	FLATHEAD RIVER	POLSON	Prestressed Concrete Stringer/Girder	1 Monolithic Concrete	25	18.897	468.172	11.734	4281	1966	0	7420
P00005116+01831	00093	STILLWATER RIVER	2M NW KALISPELL	Concrete Tee Beam	6 Bituminous	3	15.849	47.548	10.18	435	1933	1957	8990
P00005128+00531	00093	WHITEFISH RIVER	WHITEFISH	Steel Continuous Stringer/Girder	6 Bituminous	5	19.812	65.836	12.984	602	1937	0	7490
P00006049+03411	00200	CLARK FORK	1M W THOMPSON FALLS	Steel Continuous Girder-Floorbeam	1 Monolithic Concrete	7	60.96	289.255	9.022	2469	1960	0	2460
P00007043+06661	00093	BITTERROOT RIVER	3M S HAMILTON	Steel Continuous Stringer/Girder	1 Monolithic Concrete	4	25.298	92.049	9.845	786	1949	1973	5430
P00007045+00421	00093	SKALKAHO CREEK	2M S HAMILTON	Prestressed Concrete Stringer/Girder	1 Monolithic Concrete	1	25.298	26.517	29.077	706	1984	0	13510
P00007048+06151	00093	CORVALLIS CANAL	1M N HAMILTON	Prestressed Concrete Stringer/Girder	1 Monolithic Concrete	1	16.764	17.373	30.236	462	1980	0	17100
P00007049+05031	00093	BITTERROOT RIVER	2M N HAMILTON	Steel Continuous Truss-Thru	1 Monolithic Concrete	2	53.644	119.481	8.534	874	1940	0	17100
P00007082+08731	00093	LOLO CREEK	LOLO	Prestressed Concrete Stringer/Girder	1 Monolithic Concrete	2	18.288	37.49	13.868	491	1965	0	11570
P00008006+02301	00012	LITTLE BLACKFOOT, MRL	5M E GARRISON	Steel Continuous Stringer/Girder	1 Monolithic Concrete	9	17.373	140.817	8.961	1202	1958	0	2130
P00008011+08791	00012	LITTLE BLACKFOOT RIVER	1M W AVON	Prestressed Concrete Stringer/Girder	1 Monolithic Concrete	2	20.421	35.966	14.112	475	1982	0	2130
P00008013+01941	00012	LITTLE BLACKFOOT RIVER	AVON	Prestressed Concrete Stringer/Girder	1 Monolithic Concrete	2	12.801	28.041	14.112	370	1982	0	2330
P00008022+02651	00012	LITTLE BLACKFOOT RIVER	1M E ELLISTON	Prestressed Concrete Stringer/Girder	1 Monolithic Concrete	1	21.336	21.945	12.893	263	1988	0	2330
P00008043+03051	00012	GREAT NORTHERN AREA	LYNDALE AVE	Prestressed Concrete Stringer/Girder	1 Monolithic Concrete	5	15.72	62.7	10.4	652	1962	-1	16770
P00008043+03052	00012	GREAT NORTHERN AREA	LYNDALE AVE - HELENA	Concrete Tee Beam	0 None	7	13.716	62.788	12.405	570	1936	0	14640
P00008046+12211	00012	INT CAPITOL-I 15	HELENA	Steel Stringer/Girder	1 Monolithic Concrete	4	23.164	80.467	9.692	687	1961	0	13310
P00008046+12212	00012	INT CAPITOL-I 15	HELENA	Steel Stringer/Girder	1 Monolithic Concrete	4	23.164	80.467	9.692	687	1961	0	13310
P00008047+09781	00012	MONTANA RAIL LINK	3M E HELENA	Prestressed Concrete Stringer/Girder	1 Monolithic Concrete	3	32.918	84.124	30.083	2303	1978	0	18650
P00008049+03341	00012	PRICKLY PEAR CREEK	EAST HELENA	Prestressed Concrete Stringer/Girder	1 Monolithic Concrete	1	22.86	23.469	28.712	655	1978	0	18650
P00010003+05341	00087	MISSOURI RIVER	GREAT FALLS	Steel Continuous Girder-Floorbeam	1 Monolithic Concrete	9	56.388	343.509	20.482	5863	1962	1982	14730
P00010089+07281	00087	BOXELDER CREEK	BOX ELDER	Prestressed Concrete Stringer/Girder	1 Monolithic Concrete	1	21.336	21.945	13.898	288	1969	0	1580
P00010107+03321	00087	BEAVER CREEK	2M SW HAVRE	Prestressed Concrete Stringer/Girder	6 Bituminous	2	18.592	37.185	12.801	449	1966	0	2350
P00014270+03311	00012	YELLOWSTONE RIVER	FORSYTH	Steel Continuous Girder-Floorbeam	1 Monolithic Concrete	8	55.778	251.46	9.052	2146	1958	0	1040
P00014270+05031	00012	BN RAILROAD	FORSYTH	Prestressed Concrete Stringer/Girder	1 Monolithic Concrete	3	32.308	71.018	14.02	942	1977	0	1040
P00014270+08881	00012	INT WEST FORSYTH I 94	FORSYTH	Prestressed Concrete Stringer/Girder	1 Monolithic Concrete	4	26.517	78.333	14.02	1039	1977	0	1040
P00018001+00921	00059	YELLOWSTONE RIVER	MILES CITY	Steel Continuous Girder-Floorbeam	1 Monolithic Concrete	7	54.864	295.96	9.052	2526	1957	0	2090
P00020051+06421	00016	LONE TREE CREEK	SIDNEY	Concrete Continuous Slab	1 Monolithic Concrete	4	7.62	27.432	28.956	694	1974	0	12430
P00020060+00061	00200	SECOND HAY CREEK	2M SW FAIRVIEW	Steel Culvert	6 Bituminous	1	7.01	8.839	0	-1	1986	0	3170
P00023080+05591	00212	POWDER RIVER	1M SE BROADUS	Steel Continuous Stringer/Girder	1 Monolithic Concrete	4	52.425	188.976	12.893	2264	1985	0	1700
P00023080+05591	00212	POWDER RIVER	1M SE BROADUS	Steel Continuous Stringer/Girder	1 Monolithic Concrete	4	52.425	188.976	12.893	2264	1985	0	1700
P00023086+08501	00212	LITTLE POWDER RIVER	7M SE BROADUS	Steel Continuous Stringer/Girder	1 Monolithic Concrete	3	26.212	37.49	14.569	503	1976	0	990
P00023086+08501	00212	LITTLE POWDER RIVER	7M SE BROADUS	Steel Continuous Stringer/Girder	1 Monolithic Concrete	3	26.212	37.49	14.569	503	1976	0	990
P00026001+02341	00023	YELLOWSTONE RIVER	2M S SIDNEY	Steel Continuous Stringer/Girder	1 Monolithic Concrete	5	73.152	335.889	12.893	4095	1994	0	1330
P00026001+02341	00023	YELLOWSTONE RIVER	2M S SIDNEY	Steel Continuous Stringer/Girder	1 Monolithic Concrete	5	73.152	335.889	12.893	4095	1994	0	1330
P00043000+00851	00191	BIG SPRING CREEK	LEWISTOWN	Concrete Slab	6 Bituminous	1	10.363	10.363	21.336	158	1960	0	8550
P00043000+06901	00191	BIG SPRING CREEK	LEWISTOWN	Prestressed Concrete Stringer/Girder	1 Monolithic Concrete	1	12.192	12.192	19.507	186	1976	0	5640
P00052031+00211	00035	SWAN RIVER	BIG FORK	Steel Continuous Stringer/Girder	1 Monolithic Concrete	4	28.651	67.056	10.119	572	1954	0	6370
P00052049+01981	00035	FLATHEAD RIVER	2M E KALISPELL	Steel Continuous Stringer/Girder	1 Monolithic Concrete	4	71.018	268.833	14.721	3220	1994	0	8140
P00052050+04871	00035	SPRING CREEK	1M E KALISPELL	Prestressed Concrete Stringer/Girder	1 Monolithic Concrete	2	14.02	28.346	14.02	372	1966	0	13800
P00057081+09861	00087	BIG SPRING CREEK	LEWISTOWN	Concrete Tee Beam	6 Bituminous	1	8.534	9.144	24.384	156	1962	0	6820
P00057082+02191	00087	MILL DITCH	LEWISTOWN	Concrete Tee Beam	6 Bituminous	1	7.62	7.62	23.164	125	1922	0	9970
P00057326+00931	00094	DRY CREEK	GLENDIVE	Concrete Continuous Tee Beam	0 None	4	13.716	36.576	9.631	318	1959	0	10300
P00057326+00932	00094	DRY CREEK	GLENDIVE	Concrete Continuous Tee Beam	0 None	4	13.716	36.576	9.631	318	1959	0	10300
P00057327+03371	00094	YELLOWSTONE RIVER	GLENDIVE	Steel Continuous Girder-Floorbeam	6 Bituminous	8	55.778	401.726	11.033	3428	1958	0	7480
P00060094+08281	00087	MISSOURI RV, U5205, BNRR	GREAT FALLS	Steel Continuous Stringer/Girder	1 Monolithic Concrete	20	56.388	646.785	15.758	7826	1983	0	35880
P00060094+08282	00087	MISSOURI RV, U5205, BNRR	GREAT FALLS	Steel Continuous Girder-Floorbeam	1 Monolithic Concrete	27	56.388	637.946	10.911	5444	1951	1983	35880
P00062036+06701	00016	USRS CANAL	SIDNEY	Wood or Timber Stringer/Girder	6 Bituminous	3	7.62	22.86	9.204	203	1937	0	9350
P00067000+00861	00067	FRONT ST, BN RAILROAD	SHELBY	Steel Continuous Stringer/Girder	1 Monolithic Concrete	5	25.603	102.108	10.21	744	1938	0	3810
P00082005+05831	00082	FLATHEAD RIVER	3M NW BIG FORK	Steel Continuous Girder-Floorbeam	1 Monolithic Concrete	6	54.864	209.092	8.93	1530	1955	0	4290
P00098000+09741	00094	UPPER SEVEN MILE CREEK	1M SW GLENDIVE	Concrete Continuous Tee Beam	6 Bituminous	4	13.716	36.576	9.631	318	1959	0	2380
P00098000+09742	00094	UPPER SEVEN MILE CREEK	1M SW GLENDIVE	Concrete Continuous Tee Beam	6 Bituminous	4	13.716	36.576	9.631	318	1959	0	2380
S00238000+00271	00238	MILL DITCH	LEWISTOWN	Concrete Slab	1 Monolithic Concrete	2	7.62	14.935	11.887	173	1958	0	2550
S00531005+04001	00531	BITTERROOT RIVER	WEST HAMILTON	Prestressed Concrete Stringer/Girder	1 Monolithic Concrete	4	31.089	91.44	14.081	1115	1968	0	4340
U01807003+09761	01807	SEP I 15	BUTTE	Steel Stringer/Girder	1 Monolithic Concrete	4	23.774	81.076	10.972	692	1963	0	6820
U05201000+01031	05201	SUN RIVER	GREAT FALLS	Prestressed Concrete Stringer/Girder	1 Monolithic Concrete	4	38.1	154.228	33.223	4207	1980	0	13320
U05205000+04681	05205	BN RAILROAD	GREAT FALLS	Concrete Tee Beam	0 None	3	11.582	33.528	7.62	225	1934	0	6150
U05210000+00001	05210	INT CENTRAL AVE W I 15	GREAT FALLS	Prestressed Concrete Stringer/Girder	1 Monolithic Concrete	4	21.336	80.467	8.55	1864	1967	0	11250
U05210000+01601	05210	CITY ST, BN RAILROAD	GREAT FALLS	Steel Continuous Stringer/Girder	1 Monolithic Concrete	6	45.11	167.944	10.607	1433	1967	0	11250
U05210000+01602	05210	CITY ST, BN RAILROAD	GREAT FALLS	Steel Continuous Stringer/Girder	1 Monolithic Concrete	6	45.11	167.944	10.607	1433	1967	0	11250
U05210001+04961	05210	MISSOURI RV, PED TRAIL	GREAT FALLS	Prestressed Concrete Stringer/Girder	1 Monolithic Concrete	8	39.624	293.827	27.127	6090	1980	0	26320
U05710000+02421	05710	BN RAILROAD	HAVRE	Steel Stringer/Girder	1 Monolithic Concrete	30	23.469	252.374	16.123	3385	1936	1986	3560
U05710000+03821	05710	MILK RIVER	HAVRE	Prestressed Concrete Stringer/Girder	1 Monolithic Concrete	4	22.86	92.049	15.91	1234	1973	0	3560
U05802002+04741	05802	SEP I 15	HELENA	Prestressed Concrete Stringer/Girder	1 Monolithic Concrete	4	18.592	65.836	8.168	482	1962	0	7720
U05807000+06441	05807	MONTANA RAIL LINK	HELENA	Concrete Tee Beam	6 Bituminous	3	8.534	25.908	12.374	221	1934	0	16310
U05807000+07711	05807	MONTANA RAIL LINK	HELENA	Concrete Tee Beam	6 Bituminous	3	12.192	36.576	12.313	312	1934	0	16310
U05807001+08231	05807	INT CEDAR ST I 15	HELENA	Steel Stringer/Girder	1 Monolithic Concrete	4	22.25	74.371	10.302	635	1962	0	17040